HISTORICAL GEOLOGY

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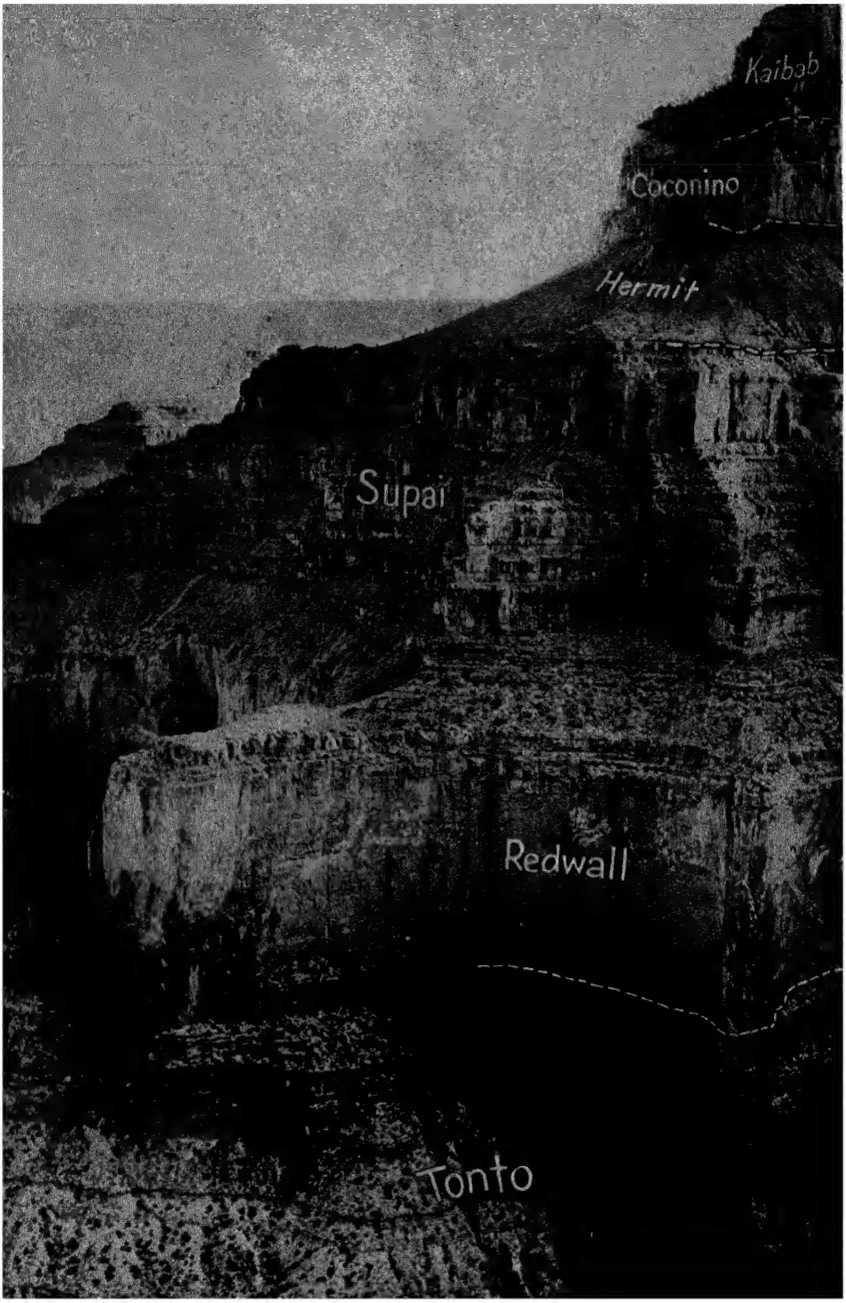

(*Frontispiece*)

Pages from the book of earth history. Marine and continental strata of Paleozoic age in the walls of the Grand Canyon of Colorado River, Arizona. (*N. W. Carkhuff, U. S. Geol. Survey.*)

HISTORICAL GEOLOGY

BY

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PREFACE

Earth history is a subject of fascinating interest and also of much practical value. The various features of the earth, the continents and oceans, the mountains and plains, and the multitudinous assemblage of organisms in the waters, on land, and in the air have not always been as they are today. The orderly succession of rock strata and their innumerable contained relics of strange animals and plants were not made to mystify man, nor were the ores of metals, deposits of petroleum, and other useful earth materials hidden away merely to test man's ingenuity in finding them. Rather, all of these things are the product of events and conditions in the past history of our planet. To know something of the probable conditions of earth origin, the almost inconceivable antiquity of the earth, the evolution of the continents, the elevation and obliteration of great mountain chains, and the remarkable record of life on the earth in past ages is to grow in understanding and appreciation of the modern world. And to acquire such appreciation is in itself a worthy end of study.

The student of historical geology, moreover, finds in this subject special opportunity for training in clear thinking, in the scientific consideration of numerous complex problems, and in reasoning from evidences or effects to the causes that produced them. An account of earth history that narrates accurately the changing conditions and events of past geologic time, but largely omits the basic observations on which the narrative depends, may hold elements of interest. The instructional value of such an account, however, is surely very far short of one in which many observational data are given and in which emphasis is laid on the deductive interpretation of these data. From the standpoint of scientific training, the means of arriving at conclusions concerning earth history are much more important than the conclusions themselves. With this in mind, the writer has undertaken in the following pages first to describe selected items of observation in connection with the geologic record and then to consider the interpretation of these items in terms of history. Uncertainties and unsolved problems are so indicated. Maps representing the distribution of sea and land at various times in the geologic past (paleogeographic maps) are largely omitted because such maps are for the most part highly subjective, the data used in constructing them are generally not evident, and the sometimes very small areas of reasonable control are not differentiated from the uncontrolled areas. Maps showing actual distribution of the systems and of the rocks of respective

eras are useful, however. These are used here and are accompanied by numerous graphic representations of typical geologic sections that show the nature and thickness of rock formations.

Historical geology is a subject of some difficulty. This is due partly to its encyclopedic scope in space and time and the breadth of its contacts with the related fields of astronomy, physical geology, physiography, biology, and others, and partly to its profusion of unfamiliar names that designate divisions of geologic time, rock formations, and fossils. These difficulties, more apparent than really formidable, cannot wholly be avoided, and it is easy to understand that, if misplaced emphasis is laid on the learning and cataloguing of a jumble of names, historical geology becomes indeed dry and uninteresting. It may be urged again, therefore, that the focus of attention should be placed on the nature of the evidences concerning past earth history and the interpretation of these evidences rather than on the necessary new names that are employed.

Experience of more than twenty years in teaching historical geology has convinced the writer that the customary organization of most textbooks on this subject is ill suited to the student's needs. Chapters on each of the geologic periods are accompanied by a more or less detailed description of the various forms of life belonging to the period. This description is commonly arranged according to the numerous biologic divisions, and in some cases according to various faunal and floral assemblages also. Repetition of this treatment in a dozen or more successive chapters almost inevitably leads to confusion and mental indigestion, the extent of which depends on the attitude and the scholarship of the student. The present book treats the evolution of life on the earth in a very few chapters which deal with entire eras or suberas. This permits somewhat fuller description of certain biologic features that are necessary to proper understanding of the life record, and the account is very much less disjointed than would be the case in separate discussions by periods. The larger divisions selected lend themselves very well to delineation of the broadly significant features in the history of life. The study of this development of plants and animals in past time is quite as important a part of historical geology, it may be mentioned, as the making of rock formations or the evolution of the continents.

Another feature of this book is the introduction of chapters that describe briefly characters of the outcrop areas of the rocks of the various eras. A geographic setting is thus provided for the succeeding more detailed consideration of the systems.

A chapter on the Historical Significance of Rock Characters develops the viewpoint of the earth historian, utilizing a remarkably wide range of geologic data that are brought together in a single region, the Grand Canyon district. This study, based on a specific area, is better than the elaboration of principles in abstract form.

Special consideration has been given to the preparation of illustrations, because clear understanding of many features in geologic history requires visual aid. Photographs and drawings, properly explained, tell a graphic story in themselves, and, although this story is in some respects more easily apprehended than the written account, it is to be studied quite as much as the material presented in the text. The use of numerous block diagrams, especially in depicting successive stages in the development of earth features, is noteworthy. The illustrations of various groups of fossils give a conception of the relative size of the types shown by using the same scale for all figures of the assembled group. The writer believes that this treatment is greatly superior to the common practice of bringing together figures of very diverse magnification or reduction so that all have roughly the same size in the illustration. Even though the scale of individual magnifications or reductions is indicated in the legend, this is difficult to visualize, and misconceptions in the mind of the student are fostered. The designation of the individual figures on the plate itself, rather than in a cumbersome legend, is an aid to the student, for an appreciable effort is required to make proper connection between index numbers or letters for figures on a plate and the explanations in the legend. This difficulty is especially evident if many figures are assembled on a single plate.

Finally, it is desirable to mention the unusually extensive aid that has been given the writer by colleagues throughout the country. This aid, in the form of counsel and criticism, has been invaluable in the elimination of inaccuracies and the contribution of knowledge of many workers in special fields.

RAYMOND C. MOORE.

LAWRENCE, KANSAS,
April, 1933.

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INTRODUCTION

CHAPTER I

THE MATERIALS OF EARTH HISTORY

Comparison of Earth History and Human History.—The writing of human history is based on the study of many kinds of records consisting chiefly of things printed or written by man. The libraries and other repositories of written matter are the main working place of the historian who describes the nature and effects of changing organizations of society, culture, commerce, warfare, and religion. In proportion as the sources of information are complete and accurate, and the labors of the historian are guided by thoroughness, keen perception, and good judgment, the account which he gives will be a true and authoritative record.

But the sources of man's history are not limited to documentary records. The graceful symmetry of a Parthenon or the beautifully modeled marble of a Venus de Milo speaks convincingly of ancient Hellenic art. The monuments and carvings in the Nile Valley tell of civilization many centuries older than that of the Greeks. Very much older still are the bone-carved representations of prehistoric creatures, primitive bronze and stone implements, and the associated remains of human beings buried in caves and river deposits. These are fragmentary but no less definite historical materials than the others. They yield information of a time that at least in part antedates the last great Ice Age when glaciers covered much of the northern continents.

The materials of earth history are comparable to the unwritten class of evidences in human history just considered. No scribe was present to write down accounts of the birth of mountain ranges, of the advance of seas over the lands, or of the strange creatures that once peopled the earth. Records of changing conditions and events are found rather in the actual remains or effects that have been preserved in the rocks. These materials of earth history are inexhaustibly rich; they occur almost everywhere. Depending only on their completeness and our ability to interpret them accurately, these records are no less explicit in their testimony concerning the earth's past than are the trappings in the tomb of an ancient Pharaoh concerning the past civilization of Egypt.

Scope of Earth History.—The beginning of the history of the earth reaches back to the birth of the earth planet—perhaps even beyond, to a consideration of the conditions that led up to this birth. Here there is common ground with astronomy, but the inception and early evolution of our planet are essential subjects of inquiry in geologic science. Properly, there is no "pregeologic history" of the earth, as indicated by some writers; this early part of earth development may, however, be designated as cosmic geology.

In the other direction, earth history extends to the present time. Here it merges with physiography in setting forth the conditions that have led to making of the earth's surface features. It is also closely connected with the fields of sedimentation, which is concerned with the conditions of formation of all kinds of sedimentary deposits; of vulcanism, which relates to activity of igneous rocks; of dynamic geology, which deals with the operation and effects of various earth forces; and of botany and zoology, which comprise the study of life on the earth. Recent geologic history overlaps human history, and the subjects of anthropology and archeology are correspondingly of interest to the student of the earth's past.

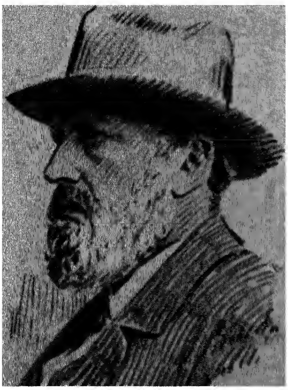


FIG. 1.—An eminent "earth historian," Edward Suess (1831–1914) of Vienna, Austria, author of the classic "The Face of the Earth."

Investigation of earth history leads to recognition of certain trends in the evolution of continents and ocean basins and in the development of life. While these afford basis for tentative conclusions as to the future, this is not in the province of our subject.

Sources of Earth History.—Construction of a true and complete account of the beginning, growth, and later evolution of the earth planet depends, as has been indicated, on the discovery and correct interpretation of actual evidences of these on or within the earth. We may say at the outset that our story will be inaccurate if the evidences that we gather are misconstrued. Furthermore, it is clear that any account must be incomplete because much desirable evidence is either lacking or so obscured that probably there will always be important gaps in our knowledge. On the other hand, the very abundance of data bearing on parts of the record makes an exhaustive consideration impossible in a book of ordinary size; indeed, completeness of this sort would be both tiresome and unnecessary to a satisfactory comprehension of significant points.

The evidences to be examined and interpreted in terms of history include (1) sedimentary deposits of many sorts and widely varying thicknesses, (2) remains of plant and animal life of former seas and lands

preserved in these sedimentary deposits, (3) igneous rock masses, extrusive and intrusive, (4) areas of metamorphosed rocks, (5) faults and folds that have deformed the rocks of the earth crust, and (6) marks of erosion by various agencies, chiefly running water and the waves of the sea. In the study of these evidences there is constant need of thorough knowledge of the principles of physical geology, for since the laws governing nature's forces may reasonably be considered to remain always the same, an understanding of the present holds, in large measure, the key to the past. We know much about the work of the wind, of running water, of glaciers, and of the sea. There is, however, much to learn of the conditions governing the formation of various types of sedimentary deposits, of the

Fig. 2.—Thickly crowded fossil shells embedded in a silty sandstone, representing a bit of sea bottom in the Miocene epoch of Tertiary time. (*W. T. Lee, U. S. Geol. Survey.*)

operation of forces that make mountains and warp continents, of the constitution of the earth's interior, and of other things that bear on earth history. Acquaintance with the structure, the mode of life, and the characteristic environment of present-day plants and animals of many kinds will contribute much to a proper understanding of the myriad fossil remains preserved in the rocks. This is primarily the province of paleontology, the science of the life of the geologic past.

The sedimentary deposits and their contained organisms form the most important part of the record of earth history. The detailed study of these deposits, involving determination of their natural units, geographic distribution, age, and interrelations, constitutes the division of geology known as stratigraphy. Extensive stratigraphic investigations furnish an essential part of the foundations of historical geology.

CHAPTER II

THE BEGINNING OF THE EARTH

Man is an incurably curious creature who for generations has sought with more or less intelligence to understand the mysteries of the world into which he is born. What is the true nature of this earth on which he lives, and of the heavenly bodies that apparently move about the earth? How were they formed? What forces have affected and now control them? The answers of ancient and primitive men are found in imaginative, often highly fantastic myths and legends, the products of superstition or religious awe. Modern science seeks to determine all possible facts concerning the earth and the universe, to classify and coordinate acquired knowledge, to ascertain relations between causes and effects, and to discover how observed conditions have had their origin. This broad field of inquiry is called cosmogony, the science of the universe.

NATURE OF THE EVIDENCE CONCERNING THE ORIGIN OF THE EARTH

Scientific inquiry relating to the origin of the earth differs to some extent from ordinary methods of research. An experiment in the laboratory may be studied closely during its progress and it may be repeated several times if desired. In the field of geology, nature assists us in understanding the relations between certain causes and their effects by continuous or frequently repeated demonstrations, as in the erosion and deposition of rock material by running water, or the construction of volcanic cones. The making of the earth, however, happened but once, and that so long ago that we might expect to find little definite evidence of causes or the manner of their production. Accordingly, consideration of this problem and of dependent matters is necessarily speculative to a degree. Yet there are some evidences and limiting conditions. These consist essentially in (1) the physical constitution of the earth, (2) its dynamic properties, and (3) its relations to other bodies in space. All of these have been inherited from the remote past.

The Earth's Form and Constitution.—The earth is a spheroid, slightly flattened at the poles and bulging at the equator, with an average specific gravity of about 5.5 and a total mass which is only 1/332,000 that of the sun. Since the outer part of the earth has a mean density of only 2.7, that of the interior must be considerably greater than 5.5. A very dense, possibly metallic core is evidenced by the manner in which earthquake waves are transmitted through the earth. The interior of the earth behaves as a solid more rigid than steel, as indicated by transmission

of earthquake vibrations, certain tidal phenomena, and astronomic determinations.

The earth is composed of 92 chemical elements, most of which occur in the form of innumerable complex combinations. A large number of these elements and some of the compounds are known in the sun. In view of evidence from physics concerning the evolution of matter, it is probable that the materials composing the earth are the same as those in the sun.

Dynamic Properties of the Earth.—The earth revolves about the sun in a nearly circular orbit and rotates rapidly in a forward direction on an axis inclined at an angle of 66.5 degrees to the plane of its orbit. These properties of motion are essentially dynamic inheritances from birth and are accordingly significant evidences as to earth origin. It is not necessarily true, however, that inclination of the earth's axis was an initial feature.

The heat of the earth—a form of the energy in it—increases downward from the surface as shown by observation, but at what rate and to what maximum in the deeper parts of the interior is unknown. A part of this heat may be an inheritance from birth, and part is undoubtedly due to pressure and physicochemical changes, a probably important part of which is radioactive disintegration of matter.

Relations of the Earth to Other Bodies in the Solar System.—The earth is one of a family of bodies (eight or possibly nine planets, about thirteen hundred known planetoids, and probably smaller masses) that revolve about the sun in the same direction and in nearly a common plane (*ecliptic*). The sun rotates in this same direction and its equator is only slightly inclined (7 degrees) to the common plane of the system. The orbits of the other planets (excepting Mercury) are nearly circular, like that of the earth, but most of the planetoids have distinctly elliptical eccentric orbits, some of which are considerably inclined to the common plane of the system.

The four inner planets (Mercury, Venus, Earth, Mars) are smaller and denser than the outer planets (Jupiter, Saturn, Uranus, Neptune), possibly excepting the newly discovered, very distant planet (or planetoid[1]) called Pluto which appears to have about the same size as the earth.

Most of the planets are accompanied by one or more moons, which (excepting the outer satellites of Jupiter, Saturn, and possibly one or two others) revolve in nearly circular orbits in the direction of the planets'

[1] It is probable that Pluto should be classed as a planetoid rather than a planet. Its orbit is decidedly eccentric like those of the planetoids and its position in relation to the four outer planets corresponds to that of the recognized planetoids to the four inner planets. Indeed, the discovery of such bodies as Pluto was anticipated by T. C. Chamberlin ("The Two Solar Families," 1928; also Chamberlin and Salisbury, "College Geology," p. 394, 1930).

rotation, and nearly in the plane of their equators. The earth's moon is exceptional in magnitude as compared to its planet and in that its orbital plane is distinctly inclined to the earth's equator (lying nearly in the plane of the ecliptic).

It is not remotely possible that these various relations in the solar system are due to chance, and we may confidently assume that the mode of origin of the earth is linked intimately with the formation of the whole planetary system. All of the bodies in the system (possibly excepting some comets and meteorites) must have originated as the result of a common cause or by some orderly process that affects the whole.

Relations of the Solar System to the Stellar System.—The sun that rules our solar system is one of several thousand million similar bodies, some larger, hotter, and brighter than others, that compose the stellar system, or galaxy. According to astronomers, this system has roughly the shape of a flattish disk, like a watch, but its size is so enormous that light traveling 186,285 miles per second requires approximately 200,000 years to cross it in the longer diameter and 30,000 years in the shorter.[1] The star that we call sun is deep in the interior of this galaxy, and the apparently dense clouds of stars that form the Milky Way mark the long way of the stellar system as seen from the sun or earth. All of the stars are moving in relation to one another with an average speed of about 70,000 miles per hour, notwithstanding the fact that remoteness makes their position appear fixed.[2]

HYPOTHESES OF PLANETARY ORIGIN

Any acceptable explanation of the beginning of the earth and of the other planetary bodies must account satisfactorily for the known facts about the system, or at any rate it must outline a rational chain of causes and effects that is not discordant with these facts. A tentative statement of such causes and effects, formulated as a guide to scientific investigation, is designated as a hypothesis. If such a hypothesis, when rigorously subjected to testing by observations, stands firmly, it may be ranked as a theory, and eventually it may become accepted as a scientific law. Because of the complexity and uncertainty of many of the factors involved in study of earth origin, all statements concerning this subject should properly be designated as hypotheses.

Two Classes of Planetary Hypotheses.—The hypotheses of planetary origin that have been proposed may be grouped in two classes: (1) those in which the beginning of the planetary system is assumed to take place as part of the evolution of a single ancestral star or nebula, without

[1] Recent studies at the Mount Wilson Observatory indicate a probable considerable reduction of these figures for dimensions of the stellar galaxy.

[2] The angular motions of the stars among each other range from less than 0.001 second to about 10 seconds per year.

intervention of any outside agency—monoparental; and (2) those in which the system is initiated by the interaction of two stars passing relatively near one another in the course of their motion through space—biparental. The monoparental type of hypothesis, which is much the older, has long dominated scientific thought as applied to various problems of earth evolution, but it encounters serious difficulties and objections. The biparental type, introduced only a little over a quarter century ago, by Chamberlin's planetesimal hypothesis, seems to offer a rational account of the possible or probable conditions of planetary origin.

The Laplacian Hypothesis

Several students of cosmogony have put forward hypotheses or have contributed to the development of the idea that the planetary system was evolved from a nebulous mass, a star, or possibly a swarm of meteorites by self-propagating causes or agencies. The names of the Frenchmen de Buffon and Laplace, of the German Kant, and of the Englishmen Herschel and Lockyer are most outstanding of those whose work, in part independent one of the other, has contributed to formulation of what has come to be known as the nebular hypothesis. Because more than one type of diffusely scattered nebulous mass may conceivably have constituted an initial stage in the making of our system, it is not really appropriate to use this name; and since one of the most explicit statements of this type of hypothesis is that of Laplace, the term Laplacian hypothesis is often used and is preferable.

The outstanding character of the planetary system is the common direction of movement of the various planetary bodies in orbits that are known to be nearly circular and that lie in essentially the same plane. Evidently, thought Laplace, these bodies, including the sun, must be residual parts of a single mass in space that initially had, or in some way acquired, the property of motion. Imagine the matter now concentrated in the sun, planetary bodies, and satellites expanded into the form of a great spheroidal nebula (possibly like one of the very diffuse giant stars). If this mass had even a slow rotational movement, the speed of rotation would inevitably increase as the diameter of the spheroid decreased through gravitational contraction, for the moment of momentum[1] of the nebula must remain constant. As the speed of rotational movement increased, the equatorial region of the spheroid must have bulged and eventually the centrifugal force might exceed the inward pull of gravity. A portion of the nebula could therefore escape outward, and as contraction continued it would be left behind, moving rapidly in a circular orbit

[1] Moment of momentum of a body may be defined as the product of its mass, the component of its velocity perpendicular to the line joining it to the center about which it revolves, and the length of this line. Recent studies in physics indicate that radiation of light and heat represent loss of mass and energy; therefore, the mass-energy total of a stellar body may slowly but steadily diminish.

about the remaining mass of the nebula in the same direction as its rotation. Laplace supposed that the material thrown off at the equator of the nebula would form distinct rings or bands. If each of the successive rings should collapse or consolidate gradually, they would form planets moving around the shrunken parent nebula in the same direction as its rotation and in a common plane. Repetition of this process through condensation of the planetary masses would give rise to the satellites. The sun represents the residual portion of the enormously compacted initial nebula. In a general way this seems almost exactly to fit the conditions observed in the planetary system, and the principle of the speeding-up of rotation with reduction in volume is sound.

There are numerous difficulties, however, and advance of knowledge concerning the planetary system since Laplace's day has brought to light various discrepancies that cannot be accommodated to the hypothesis that has been sketched. A few of these are as follows: (1) Material thrown off at the equator of the nebula would be left behind continuously and not in the form of rings. (2) The rings, even if formed, could not break down to form planetary bodies; and if they did thus condense into planets, these bodies would necessarily have a backward rather than a forward rotation, for the inner parts of the rings would be moving more rapidly than the outer. (3) The sun should be rotating on its axis at a rate enormously greater than it does, and the plane of its equator should coincide with the common plane of the orbits of the planets instead of being inclined about 7 degrees.[1] (4) Since the sun comprises all but about $1/763$ of the original nebula, practically all of the moment of momentum of the system should be found in the sun, whereas actually this belongs preponderantly to Jupiter and the outer planets. (5) The moons of Mars revolve at a more rapid rate than the rotation of the planet; some of the satellites, including the earth's moon, revolve in orbits that do not coincide with the plane of the planet's equator; and the outer moons of Jupiter and Saturn revolve in a retrograde direction. (6) The geologic implications that the earth has progressively cooled from a primitive molten state are opposed by absence of a recognizable igneous crust, by very early occurrence of glacial climates, and by other considerations. Some of these objections can be partially answered but the various difficulties necessitate abandonment or very drastic modification of the Laplacian hypothesis.

The Planetesimal Hypothesis

The failure of the Laplacian hypothesis, and of similar attempts to derive our present planetary system from unassisted evolutionary processes taking place in some ancestral star or nebula, has led in recent

[1] It may be noted that the plane of Mercury's orbit is almost exactly coincident with the inclination of the sun's equator.

years to an entirely different basic conception, for the development of which credit is due an American geologist, the late Thomas C. Chamberlin, and his astronomer colleague F. R. Moulton, both of the University of Chicago. Their planetesimal hypothesis postulates the inception of the planetary system in the effect of one star's passing somewhat near another star—our sun. Since two stellar bodies are concerned in the birth of the system, Chamberlin called this hypothesis biparental.

Disruption of the Sun by a Passing Star.—The intensely heated condition of matter in the sun signifies that it possesses a tremendous kinetic energy, which, except for the counterbalancing effect of enormous

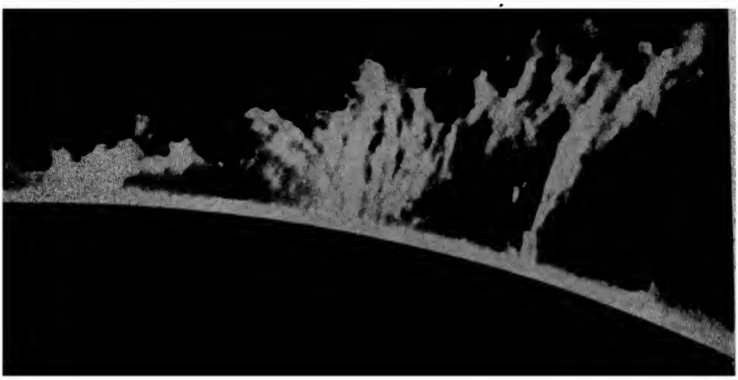


FIG. 3.—Eruptions of sun matter. These "solar prominences" extend to about 80,000 miles from the sun's surface. (*Mount Wilson Observatory.*)

gravitative pull, would result in complete disruption and escape of the sun matter. Even so, observation shows that from time to time there are apparently explosive eruptions on the sun's surface that project materials outward at great velocities for hundreds of thousands of miles. If the speed of the outwardly projected matter were sufficiently great, it would escape permanently from the sun into space, but otherwise it must fall back again.

Now in the event of some outside disturbing force, such as the gravitative pull of another star passing sufficiently near the sun to counteract in part the sun's own inward gravity, it is easily conceivable that the explosive energies in the sun would release on opposite sides of itself, in the direction of pull between sun and star, masses of sun matter that would escape outward. This lowering of the force of gravity on opposite sides is exactly the same as is witnessed in the tides raised by the moon on opposite sides of the earth. Because of the changing direction of gravitative attraction of the star at different points in its course past the sun, matter ejected from the sun would be pulled more or less strongly

out of the line of its initial motion and, on reaching the limit of its outward course, would return toward a point perhaps considerably to one side of the sun's disk. Passing onward, it would become established in an elliptical orbit about the sun. As a result of the disruptive influence of the star and the deflection of materials ejected from the sun, a swarm of sun-derived bodies may thus have been thrown into orbits of different size and shape but all moving in a common direction and in approximately the same plane. These bodies may appropriately be called planetesimals —diminutive planets. The latest statement of this hypothesis[1] suggests somewhat specific conditions and steps in the solar disruption which account for differences between the groups of outer and inner planets, for the planetoids, and for other features of the system.

Growth of the Planetary Nuclei.—The present planetary system is conceived to have been developed through gradual accretion of small planetesimals by collision with larger initial masses or nuclei. Under the conditions postulated, it is inevitable that there should have been frequent collisions and that the small planetesimals should eventually have been gathered into larger planetary bodies.

Analysis of the results of the successive impacts of colliding bodies shows a progressive tendency toward circularity of orbits and a dominance of forward rotation,[2] features that are observed in our planetary system. It is possible that a part of the rotational momentum was imparted to the original nuclei by the turbulent eruption from the sun. Organization of the system according to the Chamberlin hypothesis follows well-established principles of celestial mechanics.

Satellites.—The satellites of the larger planets are solar systems in miniature. They may represent portions of the original sun ejections that came within the gravitative sphere of control of planetary nuclei and were thrown into orbits about these nuclei. The outer moons of Jupiter and Saturn that revolve in a backward or retrograde direction may be interpreted as planetesimal aggregates that chanced to pass these planets under conditions resulting in capture.

The earth's moon is unique in the large proportion (one eighty-first) of its mass to that of its associated planet. In fact, the earth-moon may not improperly be considered as a very unequally divided double planet. Under certain conditions, involving in part a former very rapid rotation (about four hours), it is theoretically possible that the moon may have been split off from the earth, the present moderate speed of the earth's rotation and considerable distance of the moon from the earth being due to effects of tidal friction. This hypothetical fission of the earth seems

[1] See Chamberlin, T. C., "The Two Solar Families," University of Chicago Press, 1928; Chamberlin and Salisbury, "College Geology," rev. ed. by R. T. Chamberlin and Paul MacClintock, Henry Holt & Company, 1930.

[2] See Chamberlin and Salisbury, *loc. cit.*

doubtful. It is also possible that the earth and moon represent initially adjacent nuclei of unequal masses in the sun eruptions that inaugurated the system. There is question whether the remarkable craters observed on the moon's face are products of an ancient explosive volcanic stage in its history or mark the impacts of planetesimal bodies of moderately large size. The craters are nearly circular, the circumference being formed by a ring of mountains that rise in some cases 20,000 feet above the surrounding country, and the maximum diameter is more than 100 miles. The largest terrestrial craters, which are of volcanic origin, do not

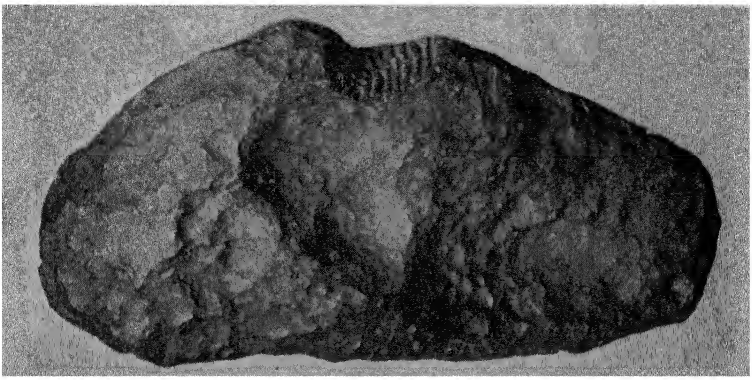


FIG. 1.—A nickel-iron meteorite from Texas weighing 1,630 pounds. (*Peabody Museum, Yale University.*)

exceed 6 or 7 miles in diameter. Meteor Crater in central Arizona, possibly formed by explosive impact of a large meteorite, is about half a mile in diameter and 600 feet deep. Since the gravity of the moon is too small to hold an atmosphere, surface features that would be destroyed quickly on the earth are preserved there indefinitely.

Meteorites.—The earth still encounters and gathers to itself solid and probably gaseous material that is moving through space. The daily infall of meteorites is several millions. Many of these meteorites are known to be related to comets, some may come from space outside the planetary system, but a large number may actually be planetesimals moving in independent orbits about the sun. Two main types are found: (1) stony meteorites, consisting of masses of crystalline rock, and (2) metallic iron meteorites, commonly alloyed with nickel and cobalt. Some are mixtures of stone and iron.

Spiral Nebulae.—First statements of the planetesimal hypothesis called attention to the spiral nebulae as probably representing the condition that existed at an early stage in the development of the solar system, after partial disruption of the sun and before any considerable concentration of the finely dispersed matter. The spiral nebulae, which are much the most abundant type of nebula in the heavens, appear to fit the

requirements since they exhibit a dominant central sunlike mass, surrounded in a plane by spiral arms of diffuse material with some denser "knots" or nuclei. It is certain, however, that the smallest of the observed nebulae are many millions of times larger in diameter than our planetary system, and evidence points to the conclusion that these spirals may actually be "universes" entirely outside our stellar galaxy. The hypothetical planetesimal nebula would be quite invisible at the distance of the nearest star from our sun.

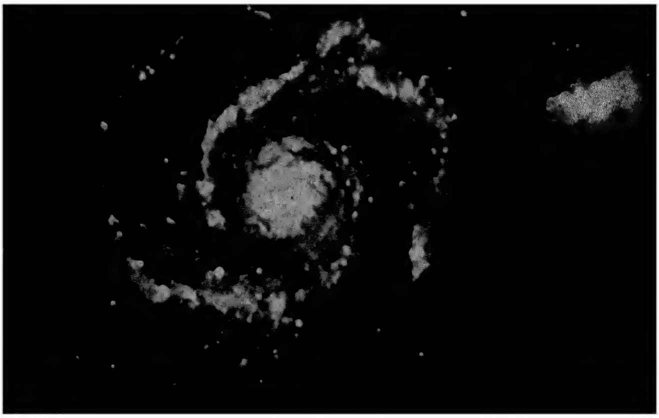


FIG. 5.—A spiral nebula showing clearly the central sunlike mass and spirally outflung arms with "knots." A form similar to this at one stage is postulated by the planetesimal hypothesis in the evolution of our solar system. (*Lick Observatory.*)

Further, an initial spiral arrangement of matter shot out by the sun bolts should almost immediately have disappeared, since, under the conditions postulated, the planetesimals were prevented from falling back into the sun only by their individual orbital motions that varied enormously in size and relative speed. While the conditions and dynamic evolution postulated by the planetesimal hypothesis appear to be entirely valid and are in reality quite independent of whatever the spirals may prove to be, we may conclude that the spiral nebulae are not planetary systems in the making.

Modifications of the planetesimal hypothesis have been advanced in recent years by Barrell, Jeans, and Jeffreys. Barrell considers the possibility of fairly rapid infall of planetesimals of such average large size that heat of impacts led to a molten-earth stage, even though the earth nucleus may have solidified originally. Chamberlin had previously considered and rejected this hypothesis. Supporting evidence cited by Barrell is found in (*a*) characters of the planetoids which he thought might represent little-changed parts of the early planetesimal system but which have an average diameter measured in miles, (*b*) the limited depth

of density variations in the earth crust, and (c) the amount of salt in the sea which seems to be much too small if oceans have existed since the earth was half grown.

A so-called tidal hypothesis developed by the British astronomer Jeans, and a modified statement of it by his countryman Jeffreys, are derivatives of the planetesimal hypothesis that differ from it chiefly in neglecting the sun's own propulsive energies, in assigning the partial solar disruption to tidal forces alone, and in postulating the almost immediate aggregation of the substance of the planets in the form of hot gaseous spheroids. There are several valid and important objections to these ideas, as pointed out by Chamberlin[1] and, since these have not been removed up to the present time, the Jeans-Jeffreys hypothesis is unacceptable.

Objection to the planetesimal and related hypotheses has been raised by some astronomers who point out that distances between stars are so great that the chance of one star's passing sufficiently close to another to have an appreciable disturbing effect on it is exceedingly remote. In fact, the possibility that another star may come sufficiently near our present solar system to wreck it and perhaps initiate a new system is about once in one quadrillion years. This may be deemed fortunate, however, and yet there can be ten thousand among the thousand million stars of the stellar system that have suffered such approaches to one another as would produce a planetary system.

SUMMARY

Evidence concerning the origin of the earth rests primarily in its inheritances of (1) chemical and physical constitution, (2) dynamic properties, comprising its motions of revolution and rotation, and (3) relation to other bodies in the solar system and the stellar galaxy. Many considerations lead to the conclusion that the conditions and events that produced the earth are responsible equally for making the other planets and the satellites.

Two types of hypotheses to account for the birth of the solar system may be recognized: one in which a single star or nebula is concerned, and the other which requires interaction of two stellar bodies. The Laplacian hypothesis, which best represents the first type, assumes an evolution of successive rings that condense to form planetary masses, and a secondary development of rings from these to make the satellites. Difficulties from both astronomic and geologic quarters require abandonment of this hypothesis.

The planetesimal hypothesis postulates the beginning of the earth and other bodies of the solar system in the disturbing effects of a passing

[1] *Jour. Geol.*, vol. 32, pp. 696–716, 1924.

star upon our sun, causing the sun to eject a small part of its mass and giving to the ejected materials an orbital motion about the sun. Development of the earth is assigned to condensation of a part of the sun-derived matter to form a core, and slow increase of size by accretion of other, probably small, masses of similar matter (planetesimals) through collisions in the course of orbital motion. The earth may thus have been a solid body ever since the condensation of the core. Circularity of the present earth orbit and the direction of rotation may be explained as effects, in part, of planetesimal accretion. Various anomalies of the solar system are satisfactorily accounted for by this hypothesis. The passing of another star near our sun is entirely possible, given sufficient time, but it is an extremely rare possibility.

CHAPTER III

DEVELOPMENT OF THE PRIMITIVE EARTH

As the nature of the newborn earth is hypothetical, so also are the critical stages of infancy and adolescence when, so to speak, habits were being formed that express themselves in features of the matured earth's face. Evidence concerning this early portion of the earth's history is obscure; and although such important features as the distribution of density in the earth, the nature of the early atmosphere and hydrosphere, the origin of the continents and ocean basins, and the governing causes of vulcanism and mountain-building belong especially to these formative stages, conclusions are largely speculative. Nevertheless, it is desirable that we give some consideration to these problems connected with the development of the primitive earth.

The Interior of the Earth.—The nature of the earth's interior has an important bearing on hypotheses to be considered in study of the development of the primitive earth.

Considered as a whole and tested by reaction to stresses of short duration (such as tides), the earth behaves as a rigidly solid, highly elastic body. Pressure and temperature increase downward from the surface, pressure at a rate directly proportional to depth (except within a possible central fluid portion where uniform hydrostatic pressure should prevail), temperature at an unknown and not necessarily regular rate.

The outermost portion of the earth comprising a shell 50 to 60 kilometers (30 to 37 miles) thick may be termed the crust. Laboratory experiments show that microscopic or submicroscopic cavities may exist in some rocks under compression equivalent to these depths but not lower. The crust is therefore the zone of fracture, in the broadest sense. Beneath the crust, where pore space in rocks cannot exist, are depths belonging to the zone of flow. The average density of the crust is somewhat greater than that of granite. The velocity of earthquake waves is observed to increase downward in the crust, but at the bottom of the crust there is a so-called "surface of discontinuity" which is marked by a comparatively sudden speeding up of longitudinal waves from 5.9 to 8.0 kilometers per second. According to measurements of the elasticity and compressibility of rocks, this indicates that the crustal portion of the earth down to about 60 kilometers (37 miles) consists of granitic to moderately basic rocks (like gabbro), in which submicroscopic and larger cavities may exist, and below this the rocks are strongly

basic (like dunite) and entirely lacking in even submicroscopic pore spaces.

Beneath the crust the velocity of earthquake waves increases rather rapidly and regularly to a depth of about 1,200 kilometers (750 miles), then somewhat more slowly to a depth of 1,700 kilometers (1,060 miles), and still more slowly until the rate becomes nearly constant to a depth of about 2,900 kilometers (1,810 miles). The remainder of the earth interior, comprising the central core with a radius of 3,450 kilometers (2,145 miles), does not appear to transmit transverse earthquake waves. Velocity of wave transmission increases with increase of elasticity and decreases with increase of density. Both elasticity and density should increase with pressure. Interpreting these observations, we may conclude that (1) the outer subcrustal zones, from a depth of about 60 to 1,700 kilometers, consist predominantly of ultrabasic silicate rocks, increasing velocity of earthquake waves being due to increased elasticity under compression downward; (2) the inner zone, from about 1,700 to 2,900 kilometers, is of similar but perhaps more basic composition, retarded increase of earthquake velocities being due to effect of very high temperature; and (3) the central core consists of very dense, highly heated matter that is inelastic and nonsolid, or, according to an alternative view, the core consists of solid metallic iron probably alloyed with nickel as in many meteorites. It is possible, also, that the 1,700 to 2,900 kilometers zone surrounding the core is made up of a mixture of metallic iron and basic silicates, the proportion of the latter increasing outward; this interpretation accords about equally well with seismologic data.

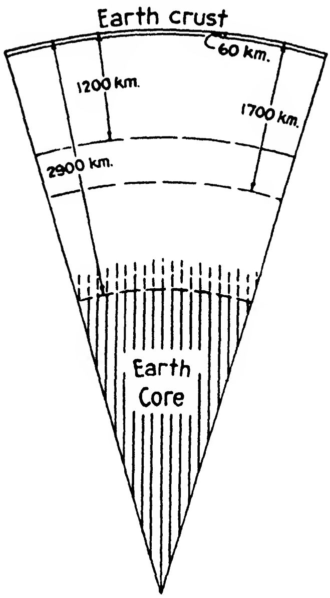


Fig. 6.—Diagrammatic section of a segment of the earth interior showing depth of zones indicated by study of earthquake waves.

GROWTH STAGES OF THE PRIMITIVE EARTH

Whatever the beginning of the earth may have been, it is reasonable to conclude that either (1) the earth was once a molten sphere of approximately its present size, or, on the other hand, (2) it was originally much smaller than now and its main development took place as a solid body. The physical and dynamic implications of these contrasting possibilities and their bearing on later earth history are most important. What were the conditions and main growth stages if the full-sized earth was formerly

molten? What factors have influenced its development if it grew to maturity as a solid body? We shall take up these questions in turn.

The Molten-earth Hypothesis

The Molten Stage.—If the earth was once a molten globe, its materials must have been free to arrange themselves according to density, much as the relatively light molten slag of a blast furnace floats on the heavy molten iron. Accordingly, the surface parts of the globe should contain the lighter constituents and the interior the heavier ones. The degree of fluidity, possible effects of liquid immiscibility, and the strength of convection currents should control the perfection of gravity differentiation.

Substances that are gases at the temperatures existent in a molten earth must have formed a hot gaseous envelope surrounding the liquid sphere, and to an unknown extent they should have been dissolved in the liquid material of the molten globe. Igneous magma is a hot liquid solution of mineral substances in other mineral substances, and considerable quantities of water vapor, chlorine, and other gases are common constituents of the solution. We may conclude, therefore, that either in the atmosphere of the molten earth or dissolved in the liquid beneath it were all of the waters of the globe, the carbon dioxide now found in carbonate rocks and coal deposits, the oxygen that has been added to rocks by oxidation, and the materials of the present atmosphere.

Formation of the Solid Earth.—Outward escape of heat may be considered to have brought about a sufficient lowering of temperature to cause crystallization of heavy basic silicates and perhaps contemporaneous solidification of a crust. Sinking of the basic silicates because of high specific gravity should result in concentration of heavy materials in deep zones of the earth interior, leaving ultimately a light magma of granitic nature in the surficial zone. Parts of the thin crust broken by tidal and other stresses should likewise sink because of the greater density of solid rock. Remelting of crystals and fragments of the crust may have occurred again and again, but eventually the earth became solid. The interior was built up of heavy constituents of the original molten globe and the crust was granitic. The granitic rocks should have been distributed uniformly over the originally smooth and featureless surface of the globe but contraction due to continued cooling is supposed to have caused a wrinkling of the crust as it shrank to fit the reduced interior.

The Atmosphere and Hydrosphere.—When the temperature of the crust fell below the boiling point of water, hot rain from the water-saturated atmosphere could begin to collect on the earth's surface, thus forming an initial hydrosphere. Continued cooling is assumed to have permitted nearly complete precipitation of atmospheric water vapor, forming a fresh-water ocean that covered all parts of the lithosphere.

Prior to the condensation of water vapor to form the hydrosphere and even after this, it may be supposed that the primitive atmosphere was very much heavier and denser than now. The chief reasons for this supposition are that in subsequent geologic time an enormous quantity of gaseous material, such as carbon dioxide, oxygen, and water, has been added to the rock substance of the lithosphere through the agencies of carbonation, oxidation, hydration, and action of living organisms. Whether the earth could hold an atmosphere many times greater than the present is questioned, because gravity—or in other words the mass of a planet—determines whether or not the rapidly moving atmospheric molecules may escape or will be retained. Furthermore, under the heated conditions of a molten globe, the velocity of molecular movement in the atmosphere would be greatly increased, and the chances of escape of molecules from the earth's control correspondingly enlarged. Since water vapor is one of the very light, active gases, most of this constituent of the hypothetical hot primitive atmosphere should have escaped into space.

If a very large part of the present atmosphere, hydrosphere, carbon dioxide of rocks, and so on, has been derived directly or indirectly by expulsion of gases from the liquid material of the molten earth, we must conclude that the gases were liberated as the liquid congealed, immediately finding way to the earth's surface or being imprisoned for a time by surrounding rock substance. Vulcanism contributes vast quantities of gases, chiefly water vapor, to the atmosphere, and the aggregate amount of volatile substances thus transferred from the earth interior during geologic time is undoubtedly of great importance. The gases of volcanoes and the gases that are found in all igneous rocks probably represent a part of the original gaseous dissolved matter that for longer or shorter time has been imprisoned in the solidified rocks of the outer earth. It is thus possible under the molten-earth hypothesis to explain the development of the atmosphere and hydrosphere as dependent largely, or perhaps mostly, on volatile materials obtained from the formerly liquid substance of the earth. In this case it is unnecessary to assume an exceedingly heavy initial atmosphere.

Problems of the Molten-earth Hypothesis.—The outstanding derivative of the molten-earth hypothesis is the fairly perfect density stratification of the globe, the surface of the lithosphere being light and the interior increasingly dense and heavy. In this the hypothesis fits well with observation. The chief problems have to do with the origin of the continents and ocean basins, the nature of the primitive atmosphere, and the causes of diastrophism and vulcanism.

Major Relief Features of the Lithosphere.—As regards the continental elevations, great mountain ranges, and oceanic depressions of the earth, it is insufficient to assert that cooling produces contraction and that this contraction causes wrinkling of the outer earth crust. Such wrinkling might form mountains but it cannot of itself produce differentiation of continental protuberances that are composed of relatively

light rocks, and ocean basins that are composed of relatively heavy rocks. Further, the total amount of crustal shortening as indicated by folded and thrust-faulted strata (including especially the highly crumpled and compressed oldest rocks) greatly exceeds any amount reasonably assignable to shrinkage of the earth from cooling.

Vulcanism may be an accompaniment of crustal deformation, but excepting possibly the heating effects of radioactivity there seems to be no adequate cause of extensive vulcanism in a globe that solidified from a molten state of approximate equilibrium.

Absence of an Identifiable Original Crust.—The absence of any rock at the earth's surface that can be recognized as part of an original crust formed by cooling has been cited as evidence opposing the existence of such a crust. It is reasonable to suppose that the original crust would not be buried everywhere by younger rocks, especially since it is clear that in some regions erosion has removed a thickness of rock amounting to several miles. In regions where the greatest sequence of very ancient rocks is exposed, it is significant that the oldest are sedimentary in origin and therefore derived from preexisting rocks. This does not preclude the possibility, on the other hand, that certain areas of granitic rocks at the earth's surface actually represent an original crust.

Ancient Climates.—Formerly it was believed that the average temperature of the atmosphere has cooled steadily from the time when the globe was molten, tropical plants in polar regions during part of past geologic time indicating climatic conditions intermediate between the extreme heat of earliest time and the cooler conditions of the present. The discovery of glacial deposits in several parts of the world representing early parts of the geologic record proves convincingly that ancient climates were not necessarily torrid.

The Solid-earth Hypothesis

The Nuclear Stage.—According to Chamberlin's statement of the planetesimal hypothesis, the initial segregation of the disrupted sun matter which was to form the earth may have been relatively small in mass as compared with the full-grown earth. At the outset the nucleus may have been gaseous or molten, but in a relatively short time it is thought to have become sufficiently cooled to solidify. Increase of size through addition of planetesimal matter is a dominant feature of what may be termed the nuclear stage, and the earth may have been a solid body throughout this time of growth. If conditions favored an early gathering-in of the heavier planetesimal matter, in accordance with causes postulated by Chamberlin, the inner parts of the earth would come to have an excess gravity and density.

The Initial Volcanic Stage.—The nature of planetesimal infall leads inevitably to heterogeneous arrangement and composition of the materials added to the earth's sphere.

The compression of the inner earth by weight of increasing thicknesses of planetesimal matter produces heat, and this, added to inherited internal temperature which may have been high, heat from impact of infalling planetesimals, and heat arising from decomposition of radioactive substances, is thought to have been sufficient, when carried outward by

conduction, to cause the melting of more fusible buried matter. This is an initiation of volcanic conditions in which the molten substances tend to work their way upward to zones of lesser heat. To the selective fusion of relatively light silicate rock matter and its transfer to the outer portions of the earth body, and to the consequent residual concentration of relatively heavy metallic alloys in the central core, is assigned the main role in establishing the density stratification of the globe. Perfection of density stratification, on this hypothesis, depends largely on the manner and the completeness of redistribution of matter through the agency of vulcanism. Heterogeneity of rock materials in the crust and interior is favored by growth of the earth as a solid body, whereas homogeneity at each level is favored by solidification of a molten globe.

The Initial Atmospheric Stage.—The original earth nucleus of the planetesimal hypothesis may have been too small to hold very much of an atmosphere. As the earth increased in mass, its capacity to hold an atmosphere became correspondingly greater, and it is assumed that the quantity of gases increased gradually. The sources of the added atmospheric constituents include (1) captured planetesimals consisting of individual gas molecules, and (2) gases contained in larger planetesimals liberated (*a*) at the time of collision or (*b*) subsequently through fusion of the planetesimal matter and transfer to the surface by volcanic action. Meteorites, and likewise almost all igneous rocks, give off gases when heated in a vacuum. Volcanoes are known to contribute large amounts of water vapor, hydrogen, nitrogen, carbon dioxide, sulphur oxides, chlorine, and other gases to the atmosphere. These observations make reasonable the assumption that gaseous matter was contained in the planetesimals, part of it being set free by heat of impacts and part being buried, forming later a constituent of the discharge from volcanic vents.

The Initial Hydrospheric Stage.—When the earth had reached sufficient size to hold an appreciable atmosphere, water vapor could be held in it; and when the point of saturation was reached, the water vapor would assume liquid form and, falling to the earth, initiate the hydrosphere. With the beginning of a hydrosphere comes the possibility of active weathering of rock materials and the transportation and deposition of sediments, which belong among the most important of geologic processes. The redistribution of matter and the making of sedimentary rocks that are effected on an enormous scale by work of water may thus have been introduced long before the earth reached mature stature.

The very ancient beginning and gradually increasing magnitude of the hydrosphere, as postulated by the solid-earth hypothesis, accompanied by selective effects of sedimentation in concentrating light materials on lands and heavy materials in water-filled basins, are possible factors in making the continents and oceans.

Problems of the solid-earth hypothesis are very similar to those of the molten-earth hypothesis but the approach to them is naturally quite different. How is the distribution of densities in the earth interior explained? Have the composition and volume of the atmosphere and hydrosphere changed greatly in the course of earth history? What is the origin of the continents and ocean basins? Why are the continents periodically elevated and what is the cause of mountain-building? What significance has the location of great mountain chains of the geologic past and present? What is the cause of vulcanism? These and many other fundamental problems of geology depend on conditions in the development of the primitive earth. The validity of the solid-earth hypothesis, or of any other, is to be tested by the extent to which it accords with evidence bearing on geologic conditions and history.

Density stratification within the lithosphere is explained as the result of (1) a tendency in early growth stages of the earth nucleus toward more rapid infall of the heavy planetesimals, and (2) redistribution of materials through the agency of vulcanism. If the effects of these are admitted qualitatively, it is still doubtful if they are adequate quantitatively.

Atmosphere and Hydrosphere.—If the volume of the atmosphere and hydrosphere increased gradually during early earth history, it is reasonable to assume that the composition of the primitive atmosphere, conditions of climate, and the nature of erosion and sedimentation were not unlike the present. This accords with evidence as far as known. It may be said, however, that, if the beginning of the hydrosphere greatly antedates the time when the earth had reached mature size, the oceans should contain much more dissolved mineral matter than they do, unless increase of water volume has been sufficient to maintain dilution.

Diastrophism and Vulcanism.—The controlling element in the periodic warping of continental areas and the sharp compression that produces mountain folding seems to be sinking movements of oceanic segments accompanied by lateral thrusts toward the continents. According to the solid-earth hypothesis, the structure of the lithosphere that is affected by this diastrophism is an outgrowth of (1) planetesimal accretion, (2) redistribution of materials by erosion, sedimentation, and vulcanism, and possibly (3) adjustments to changes in rate of earth rotation. It is not necessarily true that the size of the earth has diminished through cooling and contraction, but it is likely that this and the tendency to form denser compounds within the earth through physicochemical changes have resulted in shrinkage. This shrinkage may be a primary cause of diastrophism.

Vulcanism is closely related to diastrophism. There is seemingly greater reason for extensive volcanic activity in an earth built up of heterogeneous materials as postulated by the solid-earth hypothesis than in a planet that was formerly molten. Naturally, volcanic activity is only known, however, in the surficial part of the earth and it may be prominent where the character of rocks beneath the surface is fairly homogeneous. Vulcanism is certainly not dependent alone on composition of rocks.

These and other problems are too complex for detailed treatment here, but in the following section some attention is devoted to the important subject of the continents and ocean basins.

DEVELOPMENT OF THE CONTINENTS AND OCEAN BASINS

The continents and ocean basins, including lofty mountain ranges of the one and abyssal deeps of the other, are relief features of the lithosphere that have greatest geologic importance. The continents are protuberances rising about a half mile in average elevation above mean sea level; the ocean basins have an average depth of about 2½ miles below sea level.

These seem to be great surface inequalities, but as regards the earth as a whole they are really inappreciable. On a 5-foot globe the continents would stand only about $\frac{1}{45}$ inch above the oceanic bottoms, a difference so small as to be imperceptible; it is like a coat of varnish painted on a perfectly smooth sphere. Let us examine some of the geologic characters of the continents and oceanic areas, and hypotheses that have been advanced to explain these features.

Geologic Features of the Continents

The continental portions of the lithosphere include not only the great land areas of the globe but also the submerged borders to a depth of approximately 600 feet—the continental shelves. This modifies the outline of the continents appreciably in many places, obliterating many of the irregularities. The total area of the continental platforms comprises about 35 per cent of the earth's surface. The distribution of the continents is not regular or symmetrical, for most of the lands are contained in the so-called "land hemisphere" centering around the North Atlantic, and the seas are largely concentrated in the "water hemisphere" that includes most of the Pacific and southern Indian oceans.

The surface of the continents consists of large lowland areas and of relatively small plateau and mountain areas, the latter reaching a maximum elevation of about 5.5 miles above sea level. It is significant that the mountain chains occur typically along the border of the continents or near and roughly parallel to them.

Old-rock Platforms.—A very large part of each continent consists of an even-topped platform composed of extremely ancient igneous and metamorphic crystalline rocks. These are the very stable foundations of the continental areas. They are not now prominent topographically, nor have they been during the greater part of recorded geologic history, yet they are essentially the backbone of the continents. The pressure from oceanic segments directed against them has caused folding and faulting of rocks near their borders, forming mountain ranges, but the old-rock platforms have suffered only gentle elevation or depression accompanied by slight warping.

The old-rock platforms of the continents may be divided in two parts: (1) a dominantly emergent, so-called nuclear element, and (2) a submergent element. During known geologic history the former has tended to stand as a low but persistent land area, while the latter has been depressed slightly and flooded repeatedly by shallow seas.

Nuclear Elements.—The areas that are periodically and differentially elevated or remain relatively high are considered as *positive* portions of the lithosphere. Although the nuclear elements (also termed shields) are persistent lands, they are not an important source of the sedimentary

deposits that surround them; as outlined in later chapters there is abundant evidence that these sediments came chiefly from recurrently elevated lands at the borders of the continent. The main nuclear element of the North American continent occupies north central Canada and Greenland and is known as the Canadian Shield.

Submergent Elements.—The submergent portion of the continental old-rock platforms differs from the nuclear element only in the slight sinking or *negative* tendency that permits periodic submergence by shallow seas. Accordingly, the submergent element is covered by sedimentary deposits a few hundreds or thousands of feet (maximum

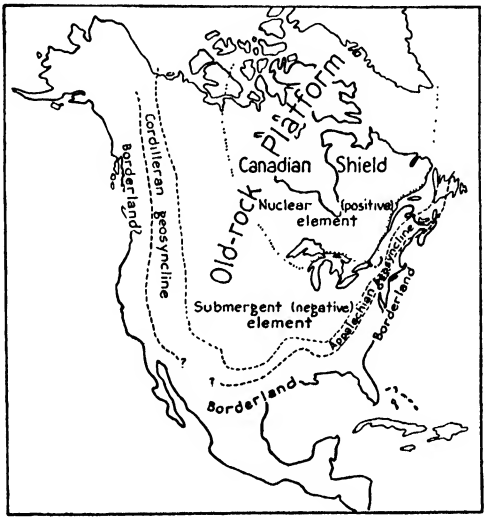


FIG. 7.—Map showing the Old-rock Platform of North America and its nuclear and submergent subdivisions. Also shown are the marginal belts of very thick sedimentation, termed geosynclines, and the borderlands that in Paleozoic time and possibly other eras existed beyond the geosynclines.

about 5,000 feet) in thickness. The sedimentary rocks are horizontal or only gently tilted, for the platform on which they rest has not been upheaved by mountain-making movements. The submergent elements of the old-rock platforms contain subordinate positive and negative areas, districts that tend slightly to rise (or sink less) and to subside (or sink more) as compared with the average.

Features of Continental Borders.—Examination of the borders of the continents calls attention to the following types of geologic relationships.

1. *Mountain Ranges Parallel to the Continental Border.*—North America furnishes the best example, with the great Cordilleran mountain belt on the west, the Appalachian chain on the east, the Endicott and other ranges in the far north parallel to the Arctic Border, and the somewhat inland east-west trending Ouachita-Arbuckle-Wichita Mountains in the south. The Pacific Ocean is largely girdled by mountain chains

that are closely parallel to the continental borders. Very certainly there is a reason for this relationship in the location of mountain chains and continental borders.

2. *Geologic Structures Discordant with Continental Borders.*—The trend of continental margins in many places, especially adjoining the Atlantic and Indian Oceans, shows no connection with geologic structure. The borders of the continents cut directly or obliquely across the axes of mountain chains and intersect the granitic and metamorphic rock areas of continental old-rock platforms. Warping and faulting, of a geologic date much younger than that of the structural elements of the continents that are thus broken off, control the position of the continental border. Africa, India, and western Europe furnish excellent examples of discordance of geologic structures and the continental borders.

3. *Continental Borders Controlled by Sedimentation.*—The outward building of sedimentary deposits forming broad coastal plains and widening continental shelves apparently controls the outline of continents in some places. Examples are seen in the Atlantic and Gulf of Mexico Borders of North America, the Arctic Border of Asia and elsewhere.

Density of the Continents.—The rock materials of the continental areas are relatively light, the specific gravity averaging about 2.6 which is equivalent to that of an average granite. Also, measurements of gravity in mountain areas indicate that these are lighter than average lowland areas.

Geologic Features of Ocean Basins

The oceans cover almost three-fourths of the surface of the globe but the area of the ocean basins, excluding the shallow continental shelf seas, is about 65 per cent of the earth's surface. The Pacific is much the largest of the oceans, exceeding by some ten million square miles the combined area of all the continents. The outline of the ocean basins, which is best observed on a globe, tends to roundness although there are numerous irregularities.

The relief features of the ocean basins include (1) the relatively steep slopes beyond the edge of the continental shelves, (2) the broad and fairly even bottom of the basins which averages about 2.5 miles below sea level, (3) swells that rise many thousands of feet above the ocean floor, and (4) elongate narrow deeps which reach a maximum depth of over 6 miles below sea level.

Slopes below Continental Shelves.—The slopes below the continental shelves are doubtless influenced in many places by sediments derived from the continents, but their location and form are believed to be due mainly to earth movements, including both folding or warping and faulting. Recent studies indicate that some of the slopes are fault scarps, the

original steepness being reduced by sediments washed over the edge of the shelves and by submarine landslides.

Ocean Floor.—The ocean floor receives an insignificant amount of sedimentary material consisting chiefly of calcareous and siliceous oozes and red clay. The attitude and depth of the floor are evidently controlled by structural conditions underlying this part of the earth crust, and also to considerable degree in some regions by accumulations of basaltic lavas.

Swells.—The swells are in some cases several thousands of miles long and a few scores or hundreds of miles wide. They suggest submarine upfolds that are analogous to the mountain ranges of continents, but they differ from the latter especially in the absence of dissection by erosion.

Deeps.—The location of the deeps, which are generally closely adjacent and parallel to prominent mountain folding on continental borders, indicates that these abysses are downwarps. They are the result of stresses in the earth crust that are connected with the phenomena of mountain-building.

Density of Ocean Basins.—The average density of rocks from oceanic areas is distinctly greater than that of the continents, amounting to about 3.3, which is equivalent to the specific gravity of average basalt.

Permanency of the Continents and Ocean Basins

There is physical and historical geologic evidence for the conclusion that the continents and ocean basins are essentially permanent features of the lithosphere as regards both general structural character and location. The outlines of the continents and basins have been modified by outward building of the continents, by development of mountain belts through lateral compression, and by the sinking of fragments of continents into oceans. There has been no general interchange of continental and oceanic areas, however. This conclusion is indicated (1) by the difference in average specific gravity of the continents and ocean basins which is primarily responsible for the general elevation of the land areas and depression of the oceanic areas. No considerable change of continent to basin or basin to continent could be effected without reversal of specific-gravity characters. (2) Shallow seas have repeatedly spread over parts of the continents, but these are not at all parts of the oceans in the strict sense. The fact that sediments of deep-sea type are practically unknown on the lands and the observation that the marine deposits of the continents are all of comparatively shallow or very shallow waters support the conclusion that the continents have been continents throughout at least the part of geologic time that is recorded by sedimentary rock formations. Deposits of abyssal type occur in the Mediterranean, East Indies, and West Indies, all of which regions offer evidence of

unusual vertical movements; they belong to a belt of great crustal mobility.

Hypotheses of the Origin of Continents and Ocean Basins

The beginning of the continents and ocean basins belongs to so distant a part of the geologic past that the causes and early evolution of the major relief features of the lithosphere are shrouded in obscurity. A few of the hypotheses that have been offered to account for the continents and oceans will be considered briefly. Some are predicated on the supposition that the full-sized earth was formerly molten, some postulate a partial or potential fluidity of the interior in late geologic time, and some are based on the concept of a globe that developed as a solid body. Like the problem of the beginning of the earth, that of the origin of continents and ocean basins cannot now be given definite answer.

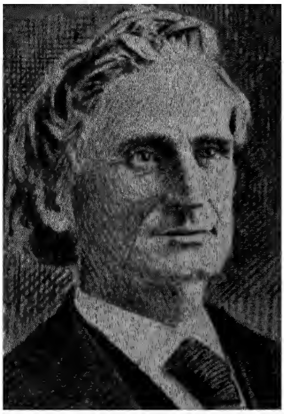


Fig. 8.—James Dwight Dana (1813–1895).

Differential-contraction Hypothesis.—A suggested mode of origin of the continents and ocean basins in the course of cooling and solidification of a once-molten planet is based on assumed differential contraction of various segments. In the words of James D. Dana, one of the foremost American geologists of the last century, this hypothesis may be stated as follows.

> The defining of the continental and oceanic areas began with the commencement of the earth's solidification at the surface. The continental areas are the areas of least contraction, and the oceanic basins those of the greatest, the former having earliest had a solid crust. After the continental part was thus stiffened and rendered comparatively unyielding, the oceanic part went on cooling, solidifying, and contracting throughout; consequently it became depressed, with the sides of the depression somewhat abrupt. The formation of the oceanic basins and continental areas was thus due to unequal radial contraction.

Basic-eruption Hypothesis.—A hypothesis of the origin of continents and ocean basins developed by the late Joseph Barrell of Yale University postulates an original granite crust that was formed by cooling of a molten earth. The crust was continuous and uniform over all of the globe, and in the beginning its surface was featureless. Accumulation of heat from radioactive sources is thought to have caused a slow remelting of solid basic rocks in parts of the subcrustal zone, and the eruption of heavy magma into and through the granitic crust on a gigantic scale is assumed to have weighted down broad areas of the crust. The

subsided segments of the crust form ocean basins and the residual undepressed segments comprise continents. As suggested by the lava plains of the moon, it is conceived that basic eruptions, when started at a certain point, extend outward with widening radius, giving rise to the rudely circular outlines that are characteristic of ocean basins.

"Floating-continents" Hypothesis.—Another hypothesis is that of "floating continents," recently introduced by a German meteorologist (Wegener), primarily in order to account for distribution of past climates and other geologic features. This hypothesis, which has many adherents, especially in Europe, postulates a single large initial continent formed by the floating together and piling up of the lightest surface constituents of the formerly molten globe. Comparatively late in geologic time,

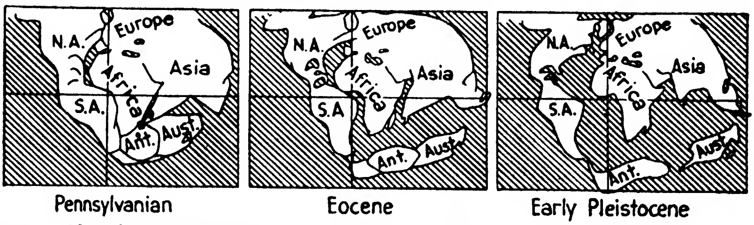


FIG. 9.—Sketch maps showing hypothetical relations of the continents at three past stages. The horizontal line in the central part of the maps represents the Equator, and the vertical line an arbitrary meridian that holds the same position across Africa. Note the assumed lateral shift of other land masses, especially the "drifting" of the Americas away from the Old World. (*Redrawn from Alfred Wegener.*)

very long after solidification of the earth, this primeval continent is assumed to have broken apart, the several fragments shifting their position laterally through tidal action and the yielding of a hypothetical subcrustal zone of heavy weak rocks that cannot resist differential pressure. The Americas are thus supposed to have "floated" westward from their former connection with the Old World, the great range of mountains along the Pacific Border being formed by the lateral pressure encountered by the continents in their movement. The suggested cause of the supposed drift appears to be quite inadequate, especially where northward or southward migration must be assumed. Also, if the substratum is sufficiently mobile to permit large-scale shifting of continental masses, it is difficult to see how it is resistant enough to form great mountain ranges; or viewed oppositely, if resistance is sufficient to form such mountains, it is hardly conceivable that any shifting of the continents is possible. There are many other objections which have led most geologists to reject this hypothesis.

Segregation Hypothesis.—Application of the planetesimal hypothesis to the problem of the origin of the continents and ocean basins has been developed by Chamberlin in what may be termed the segregation hypothesis. This is based (1) on conditions of eruption of sun matter that formed the earth nucleus, which are assumed to have produced an

initial difference in the average density of opposite portions of the primitive earth. This difference is regarded as a main factor in the concentration of most of the continental areas of the mature earth in the so-called "land hemisphere" and oceanic depressions in the opposite "water hemisphere." (2) Attention is directed to the mechanics of atmospheric circulation about a rotating sphere, in which three alternating areas of high and low pressure are developed in each hemisphere, as is observed on the earth at the present time; the effect of atmospheric circulation on the concentration of lighter planetesimal material at certain places is assigned as a differentiating factor that in the course of planetary growth led cumulatively to development of slightly lighter (continental) segments and slightly heavier (oceanic) segments. (3) Accompanying and following this initial segregation, the concentration of light siliceous matter on the lands through solution and removal of heavy basic matter to the ocean basins is considered as a further factor in making the continents. (4) The effect on a solid earth of possible changes in the rate of rotation is analyzed by Chamberlin and compared with the location and pattern of the continents. The details of this hypothesis are too numerous and complex for presentation here. It should perhaps be noted that the role of these processes is the primary differentiation of the earth surface into continental and oceanic areas. (5) The accentuation of continents and ocean basins is attributed to later diastrophism and vulcanism in which the continental and oceanic segments have behaved differently, the latter sinking the most.

Asthenolith Hypothesis.—The light, elevated portions of the lithosphere that form continents, and the heavy, relatively depressed portions that form ocean basins, consist primarily of igneous rocks, for the discontinuous veneer of sedimentary materials is quantitatively insignificant when the earth is considered as a whole. The igneous rocks of the continents belong predominantly to the granite family, consisting of acid-rich light rocks; the igneous rocks of ocean basins belong almost entirely to the basalt family, consisting of basic heavy rocks. The problem involved in explaining the existence of continents and ocean basins, therefore, may be largely a question of the distribution in the earth crust of igneous rocks of different density.

According to a hypothesis recently advanced by Bailey Willis, the chief factor in the concentration of granitic rocks in certain crustal areas and of basaltic rocks in others is the formation of horizontally extensive, lenticular bodies of igneous magma at or near the base of the crust, that is, some 30 miles or more beneath the surface. These large magma bodies, named asthenoliths, are thought to result from melting of parts of the subcrustal zone due to accumulated heat derived from the earth interior. The rise of temperature beneath the crust is caused by the relatively low conductivity of the crust, which is thus unable to carry

heat outward as rapidly as it is supplied from the interior. Irregularity in the amount of outwardly transferred heat and its effects in different places is assumed to result from heterogeneity of materials within the earth and from the distribution of local melting caused by action of tidal and other stresses in the deep rock zones surrounding the highly heated core. When subcrustal temperature in some region is sufficiently increased, melting is initiated.

The composition of a growing asthenolith is more or less basic because this is the average character of the rocks beneath the crust. Subsequently, however, as the dimensions of the melted mass are slowly increased, ultimately reaching a horizontal extent of perhaps some hundreds of miles, differentiation of the magma into light (granitic) and heavy (strongly basic) portions is extremely probable. Such differentiation is known to be the normal habit in large magmatic masses.

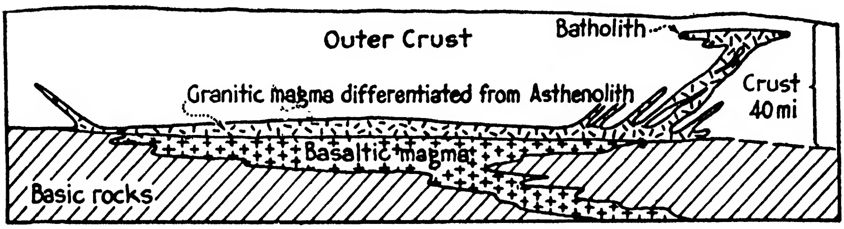


FIG. 10.—Diagram of an asthenolith showing differentiation of the magma into lighter (granitic) and heavier (basaltic) portions. (*After Bailey Willis.*)

Analysis of structural conditions gives theoretical basis for the conclusion that eruption of granitic magma is especially favored in the peripheral portions of an asthenolith. This adds light matter to parts of the crust adjoining the asthenolith and concentrates distribution of granitic rocks to form continents. The area of the asthenolith becomes relatively denser and, through sagging of the crust, oceanic depressions are developed. Large eruptions of basaltic magma may occur in the depressed areas. The transfer of light matter from oceanic to continental areas is presumably compensated by movement in the zone of flow of heavy matter from continental to oceanic areas, this movement taking place in the subcrustal zone.

The grouping of continents in the land hemisphere is regarded as consequent on an original concentration of lighter materials in a part of the globe as postulated by Chamberlin.

It is observed that many of the ocean deeps, which represent subsiding areas of the crust, are adjacent to areas of strong elevation and vulcanism on land. A genetic relation between these features is strongly indicated. The asthenolith hypothesis accounts for the depression as a sag of the crust over the central part of a subcrustal magma, and the continental

elevation and vulcanism as a result of eruption toward the margin of the magma.

SUMMARY

The extremely long and geologically critical stages of earth development that lie between the birth of the planet and the beginning of the historical record contained in exposed rock formations are mostly subjects of speculation. We may conclude, however, that these stages are associated either with (1) an initial mature-sized molten globe, or (2) an earth that grew up as a solid body.

The *molten-earth hypothesis* provides basis for a nearly perfect density stratification of the lithosphere, with heaviest materials in the center and lightest at the surface. The primitive atmosphere must have been many times denser than now, containing all of the gases that now form the hydrosphere and certain compounds in the lithosphere, which is unlikely; or, on the other hand, most of these gases must have been dissolved in the liquid rock matter and liberated subsequently. There was no hydrosphere until surface temperatures fell below the boiling point of water. It is hard to explain how the major surface irregularities of the lithosphere have been formed if the earth was once molten. The continents are not only higher but they are distinctly lighter than the ocean basins. Contraction due to cooling might cause wrinkles (mountain ranges) but the observed evidence of crustal shortening greatly exceeds that assignable to cooling. An original earth crust is not identifiable. As regards the known geologic record, ancient climates were not uniformly hot, for glacial deposits of great antiquity are known.

The *solid-earth hypothesis* postulates gradual increase of size from an initial nuclear stage. Infalling planetesimal matter was necessarily arranged in a heterogeneous manner. Heat from condensation and other causes brought about fusion of parts of the buried substances, introducing a volcanic stage. This vulcanism is assumed to have developed a rough stratification of materials according to density. The atmosphere consists of gases coming from the original nucleus together with later additions from planetesimals; initially the atmosphere may have been very much lighter than now. The hydrosphere could begin to exist as soon as the atmosphere became saturated with water vapor; in the beginning the hydrosphere may have been small. Weathering of rocks, transportation of detritus, and sedimentation are mainly dependant on work of water and, if a hydrosphere was present long before the earth was fully grown, it is possible that sedimentary rocks are not confined to the outermost part of the earth.

The *development of the continents and ocean basins* is an especially important problem that belongs to the primitive stages of earth growth. The continents stand about 3 miles above the floor of the ocean basins;

they are composed of relatively light materials. The most stable portions of the continents are areas of ancient crystalline rocks called the old-rock platforms. Persistent land portions of the platform are the positive or nuclear elements; portions covered by shallow seas are the negative or submergent elements. The continental borders consist of mountain ranges parallel to the border, of various geologic structures that are discordant with the border, and of areas dominated by sedimentation. The ocean basins contain swells and elongate, narrow deeps, but most of the floor has an even depth of about 2.5 miles below sea level. The rocks underlying the oceanic areas are materially heavier than those of the continents.

Difference in specific gravity of the continental and oceanic areas and the fact that marine deposits on the continents are of shallow-water type, abyssal deposits being unknown except in a few places of great crustal mobility, indicate that the continents and ocean basins are essentially permanent features of the lithosphere.

Among hypotheses of the origin of continents and ocean basins are (1) the differential contraction hypothesis, which assumes initial solidification of continents and greater contraction of oceanic areas; (2) the basic eruption hypothesis, which explains the ocean basins as parts of an original granitic crust that are depressed by weight of heavy rock erupted from beneath the crust, and the continents as undepressed parts of the crust; (3) the floating-continent hypothesis, which postulates the lateral migration of the Americas westward from a former connection with the Old World; (4) the segregation hypothesis which suggests a control for partial segregation of light planetesimal matter in continental areas and heavy in oceanic regions, with further differentiation of light and heavy earth segments through effects of weathering, vulcanism, and diastrophism; and (5) the asthenolith hypothesis, which accounts for concentration of granitic rocks in continents and basaltic rocks in ocean basins through the agency of large subcrustal "blisters" of igneous magma.

CHAPTER IV

THE HISTORICAL SIGNIFICANCE OF ROCK CHARACTERS

We may best begin our study of earth history, as recorded by the accessible rock formations of our planet, by first examining the nature of the records. These are, in essential character, results or *effects* from which we must reason back to *causes*. Like a detective who with trained eye searches for all possible evidences bearing on a crime and from these evidences constructs answers to the questions when, how, why, and by whom the crime was committed, so the geologist seeks for evidences in the rocks, undertaking to determine when, how, and by what agency certain conditions and events in earth history were brought about. The trustworthiness of inferences concerning geologic history depends on completeness of evidence, thoroughness of observations, and accuracy of reasoning. This last factor is especially important. In it lies one of the main educational values of historical geology. There is probably no branch of geologic science more interesting or appealing to the imagination, and at the same time there is perhaps none requiring more constant and careful exercise of reasoning powers.

THE GRAND CANYON REGION AS AN EXAMPLE

The principles of historical interpretation, which are the main theme of this chapter, might be presented as dry statements of general abstract "laws." It is better, however, to base consideration of the subject on some definite region that offers many excellent examples of "historical evidences." Such a region is that of the Grand Canyon of the Colorado River in northern Arizona. Probably nowhere else can one find greater variety of significant historical evidences more clearly shown, and nowhere else can a single view cover such a wonderful vista of geologic time. A visit to the canyon can hardly fail to arouse interest in the colossal scale of sheer cliffs, the endless intricacy of architectural carving, and the brilliance of nature-painted colors, but for us these are all secondary to the geologic history that the canyon and the rocks reveal.

Significance of Physiographic Characters

Let us consider first the history of making the Grand Canyon. The canyon and other surface features belong to a very late chapter in the history of the region, for the rock strata must have been made and the plateau character of the country must have been attained before any

possibility of a canyon could exist. Study of recent geologic history thus takes account of physiographic characters. We know for certain that the work of canyon making is still going forward, for a glance at the coffee-colored, sediment-laden river indicates that a tremendous quantity of rock debris is constantly being carried away. A single storm plucks boulders and great quantities of smaller rock fragments from the canyon walls and sweeps them down the gullies and side canyons to the river. Trails are washed away. The aggregate volume of material moved by a hard rain is enormous.

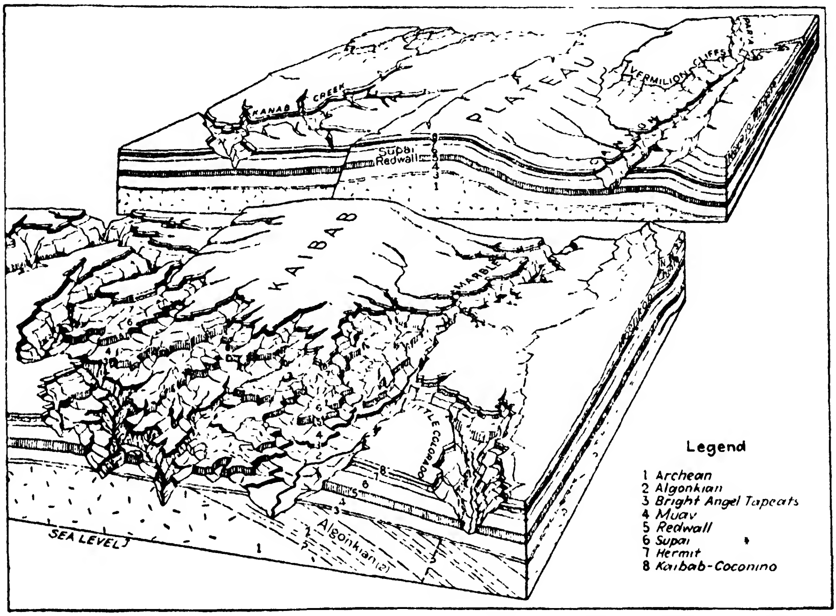


FIG. 11.—Block diagram of a part of the Grand Canyon district showing physiographic and structural features to the canyon. Note in the upper right-hand part of the drawing that the post-Kaibab formations which make the Vermilion Cliffs are parallel to the Kaibab beds, and that all of the stratified rocks here are gently folded alike. (*R. C. Moore U. S. Geol. Survey.*)

The effectiveness of the work of running water in carving the rocks of the Grand Canyon and in transporting the derived sediments seaward cannot be questioned, but the making of a depression 10 to 15 miles wide, a mile deep, and some 285 miles long, not to mention the tributary canyons, seems an incredible task. Given sufficient time, however, it is evident that forces now at work could have accomplished it. If the total volume of rock excavated and the average amount of material transported annually by the river is measured, the time required for the formation of the canyon can be computed. It is assumed, in this case, that conditions of rainfall and other factors have remained essentially the same as now. Such computation cannot be accurate, but it gives

results indicating that the beginning of the canyon dates back more than a million years. Since the carving of the canyon is a very recent episode in the history of this region, we begin to comprehend the immensity of geologic time.

Examination of the location of the Colorado River canyons with reference to the distribution and structure of the various rock formations of the plateau country and the discovery of remnants of peneplains at high levels in several places lead to recognition of a number of stages in the physiographic history of this region that antedate the beginning of the Grand Canyon. The subject is too involved and too little related to objects of the present study to call for discussion here, but it is important to note that all physiographic features have some historical meaning. Accordingly, the record of recent geologic time is commonly clear and detailed. The land surfaces of ancient geologic times are unfortunately obliterated mostly, and historical inferences based on the remaining very fragmentary physiographic evidences are, therefore, less definite and less complete.

Analysis of the Rock Record

When we contemplate the rock formations in the Grand Canyon region, we have to do with relatively ancient geologic history. One of our first observations is that almost all of the rocks are stratified. There are great layers of hard cliff-forming rock that stretch as far as the eye can see. Alternating with the cliff-making beds are softer strata that form slopes and benches. The relative thickness, color, and topographic characteristics of the outcrops make it easily possible to distinguish and trace the different hard and soft groups of strata. The persistence and general uniformity of individual parts of the stratified series indicate that the conditions of making each of them must have been very similar throughout a large territory. There are innumerable changes in the character of the rocks vertically but there is uniformity horizontally. Let us begin at the top of one of the trails that descend in steep zigzags from the canyon rim and examine more closely the rocks so clearly exposed to view. The special object of this study, it should be recalled, is the making of observations on the nature of historical geologic evidences and the manner of interpreting them.

Limestone of the Canyon Rim.—The first several hundred feet of descent into the canyon take us down across thick layers of resistant gray or creamy limestone. This is the rock that caps the plateaus for thousands of square miles. The limy character of the formation, its even bedding, and general uniformity over a wide area indicate that calcareous sediments were deposited in a large body of standing water. Conditions were essentially uniform for a time sufficient to permit accumulation of some hundreds of feet of calcareous mud which later

solidified to make the rock. That the water body in which these sediments were deposited was part of an ancient sea, rather than an inland lake, is proved by the presence of numerous remains of marine organisms. These consist chiefly of the well-preserved shells of shallow-water marine invertebrates. General absence of clayey matter in the limestone leads

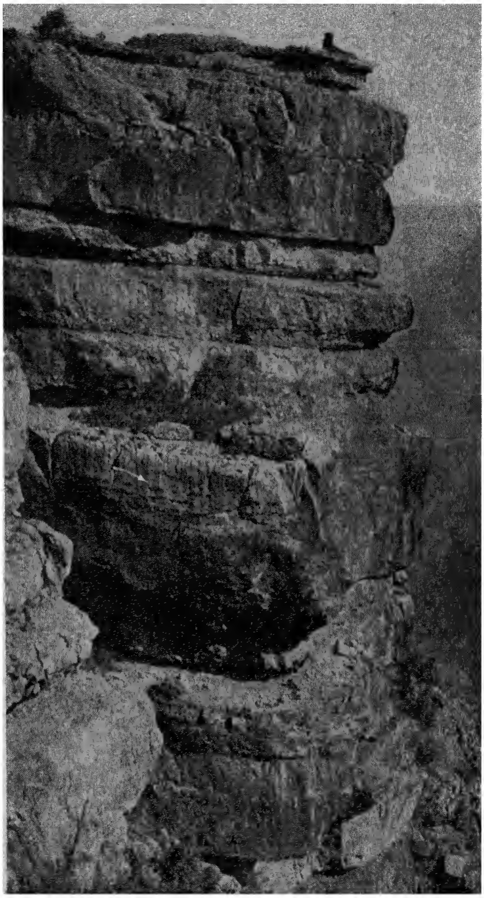


FIG. 12.—Kaibab limestone, near Hance Creek, Grand Canyon. This view shows well the thick layers, some harder and more uniform than others. Nodules of chert may be seen in the topmost beds and in the thick bed near the center (arrow). (*J. K. Hillers, U. S. Geol. Survey.*)

to the conclusion that the sea was fairly clear. Furthermore, we may infer that the lands bordering the sea were either distant from the point of our observation or that they were so low and perhaps so covered with vegetation that the streams brought no large quantity of land-derived detritus into the basin. We do find some sandy layers, however, especially in the lower part of the limestone, which indicates that

somewhere in the neighborhood there must have been a source of sand. The sand was spread by waves and currents over the sea bottom. The calcareous substance of the rock was deposited by the action of organisms and probably also by chemical precipitation of dissolved calcium carbonate in the sea water. Parts of the formation contain a profusion of chert nodules, which, being more resistant to weathering than the limestone, form rough projections scattered over the rock surfaces or accumulate as a loose rubble on the ground. This chert represents the siliceous impurities originally deposited with the calcium carbonate but later segregated by chemical action in concretionary masses in the rock. These observations enable us to conclude that what is now a lofty plateau was formerly below sea level and also make it possible for us to determine some of the conditions that existed in the sea in which the limestone was deposited.

Stratigraphic Divisions and Nomenclature.—The limestone strata that we have just considered comprise a geologic *formation,* that is, rock beds having similar lithologic characters, fossils, and representing essentially uninterrupted deposition of materials under like conditions. Such an assemblage of rock layers is the natural unit of geologic mapping. Accepted practice among geologists requires that each geologic formation shall have a name derived from a locality, and this becomes, therefore, the *type locality.* The same name cannot be applied properly to two formations or other stratigraphic units, and the application of a name as first published has priority.

The formation that makes the rim of the Grand Canyon and the cap rock of much of the surrounding plateau was named by N. H. Darton, of the United States Geological Survey, who selected the name Kaibab limestone, from the Kaibab Plateau on the north side of the Grand Canyon. Clearly, it would be undesirable and confusing to apply the name Kaibab to some other division of strata. If, on the other hand, different names are employed in different areas for what later proves to be one and the same formation, then the first designation published should replace the others. In early geologic writing many formations were given a simple descriptive term, such as Old Red sandstone, First Magnesian limestone, and Corniferous (horn-bearing) limestone. Such names are now replaced by geographic terms, such as Catskill, Joachim, and Onandaga.

Occasionally it is desirable to distinguish one or more parts of a formation, which are designated as *members,* or, if rather local in distribution, as *lentils.* A member may have special economic importance, as the Roberts iron-ore member of the Rochester formation; it may be prominently expressed in the topography and thus serve as an aid in mapping; or it may be distinguished by special paleontologic, lithologic, or other characters.

Upper Cliff-forming Sandstone.—Beneath the Kaibab limestone is a prominent, light-colored sandstone, some 350 feet thick, that is called the Coconino sandstone. Almost everywhere it forms sheer cliffs. Examination of the rock shows that it is fine-grained, very uniform in character, and cross-bedded on a huge scale. The sand grains are mostly well rounded and some of them show frosted surfaces. The inclination of the cross bedding is fairly uniform in amount and direction. Evidently the sand was deposited by agencies that shifted the sand grains along to the lee side of slowly advancing bars or dunes, as is indicated by the inclined bedding. Whether the sand is that of bars, indicating accu-

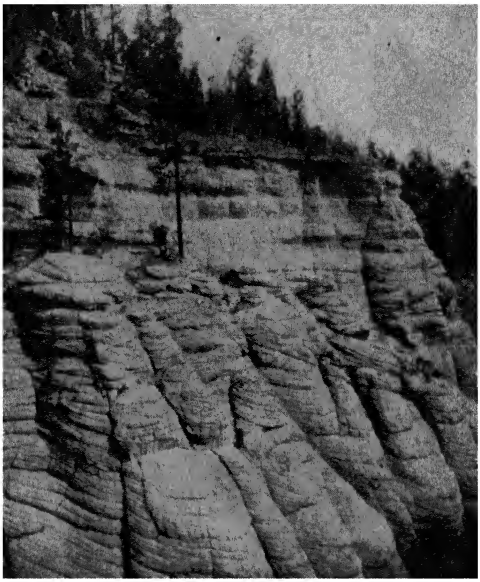


FIG. 13. Coconino sandstone, Walnut Creek, near Flagstaff, Ariz. This formation is distinguished by its light color and prominent cross-bedding (*N. H. Darton, U. S. Geol. Survey.*)

mulation under water, or represents an ancient desert in which the action of the winds produced great dunes and removed all rock materials finer than the sand, is an unsolved problem. General uniformity of the angle and direction of slope of the cross-beds suggests the former concept, whereas the degree of rounding and frosting of the sand grains, their size and grading, and other features suggested by comparison with known eolian deposits favors the latter interpretation. Interesting additional evidence relative to the origin of the sandstone has recently come to light in the discovery at many places in the Grand Canyon area of sharply impressed fossil footprints on inclined bedding planes in the lower middle part of the formation. These prints prove the existence of a variety of four-legged creatures, large and small, whose average size is

about that of a small cat. Strange to relate, almost every one of the many scores of trails show that the animals were climbing up the steep sand slopes, but not down! Furthermore, observations indicate that sharply defined footprints are not made in dry sand or in sand under water but are best developed in moderately moist sand. Rain might supply the moisture, but the very smooth bedding planes show no rain prints. The occurrence of tracks on numerous succeeding bedding planes calls for rather regularly recurrent wetting. Hence, for the present, we are left in doubt as to the conditions under which the tracks were made

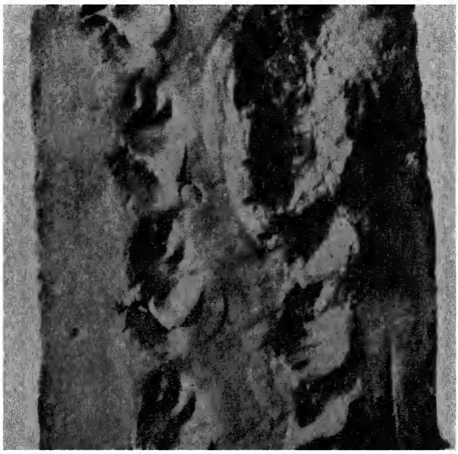


Fig. 14.—Fossil tracks on a slab of Coconino sandstone from the Grand Canyon. Note the "push-outs" behind each footprint. These were made by slipping of the sand under weight of the animal as it climbed the slope of the inclined bedding plane. (*C. W. Gilmore, U. S. National Museum.*)

and in regard to the mode of origin of the Coconino sandstone. By no means all of the pages in the geologic record are as yet translated clearly.

Red Beds.—The formation next below the Coconino sandstone is a very soft, dark-red sandy shale containing layers of shaly sandstone. It is called the Hermit shale. The average thickness of this formation is about 350 feet. In marked contrast to the hard rocks that occur immediately above and below it, the shale forms rather gentle slopes. In parts of the canyon where erosion of this weak zone has caused a considerable retreat of the cliffs above, a wide bench, known as the Esplanade, is produced.

At the very top of the red shale, we find evidence in several places that this formation must have been exposed to weathering and probably some erosion before the deposition of the overlying sands began. This is shown by a peculiar discoloration and other changes in lithologic character of the uppermost Hermit beds, and especially by the occurrence in the shale of cracks filled with Coconino sand. In some cases these cracks

are a foot or more in width and they reach downward several feet into the shale. Possibly the variations in thickness of the red shale in different parts of the canyon area are partly due to erosion that preceded deposition of the Coconino formation. Certainly there is evidence of a great change between conditions recorded by the horizontally stratified red beds and those indicated by the overlying light-colored, cross-bedded sandstone. There is evidence, further, of an indefinitely long time that is not represented by deposition of sediments. This record of the break in the succession of beds is a disconformity.

The deep-red color of the Hermit beds is due to thoroughly oxidized iron disseminated through them. Iron is a common constituent of rocks,

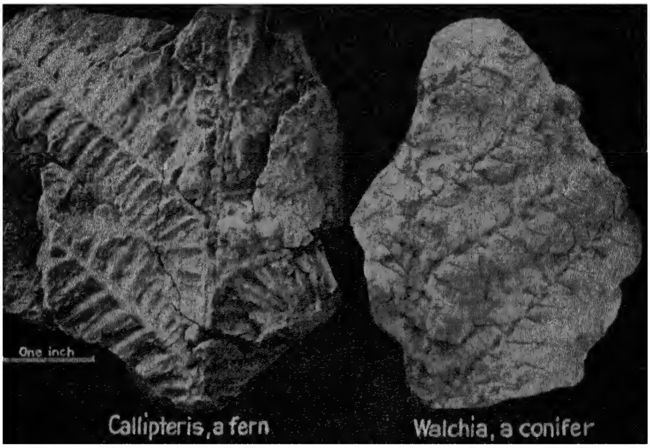


FIG. 15.—Fossil land plants from the Hermit shale. They are not very well preserved but are clearly recognizable as plant remains. (*David White, U. S. Geol. Survey.*)

and the oxidation of iron to this red form is a typical result of weathering under conditions that promote chemical decay. Thorough oxidation of the iron in rocks is commonly found in moist tropical climates, in temperate climates where there is frequent alternate wetting and drying, and under certain conditions in arid climates. Red sediments may possibly be derived also from the erosion of previously formed red deposits.

The rather even horizontal bedding of the shale shows that the sediments were spread out either under water in a broad shallow basin, or else by sluggish streams on a very wide, flat plain. Layers showing mud cracks, the presence of land plants, footprints of vertebrates, and the absence of marine fossils point to fluviatile deposition. The sediments were exposed above water at various times, and conditions were apparently favorable to thorough oxidation. All factors being taken into account, it seems likely that these beds represent stream-made deposits, formed in a temperate, moderately dry climate.

The lower boundary of the Hermit formation is locally very uneven, as is evidenced by the sand- and shale-filled hollows, 40 feet or more in depth, that cut downward into the underlying strata. These depressions were carved by erosion before the beginning of sedimentation during Hermit time and therefore afford proof of another break in the stratigraphic record. Not only is there an interval of geologic time of undetermined magnitude during which no sedimentary record was made in this region, but also there is evidence of the removal of an unknown thickness of the pre-Hermit rocks. Such a disconformity represents, therefore, a "lost interval" in the history of the area.

The formation next below the Hermit shale is called Supai. It consists of thick-bedded, reddish to yellowish sandstone and interbedded sandy shale and, in the lower part, some impure limestone. The thickness of the formation is nearly 1,000 feet. The sandstones are commonly cross-bedded, showing the existence of fairly strong currents that

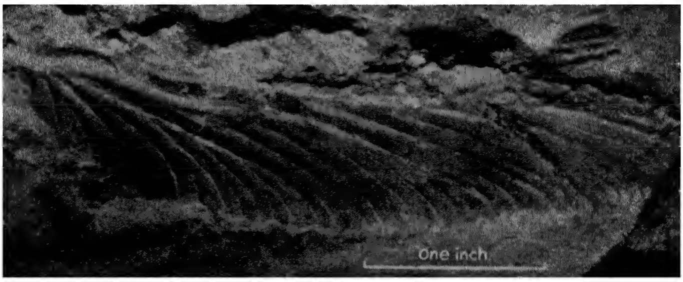


FIG. 16.—Fossil wing of a dragon fly (*Typus*) found associated with the Hermit shale plants. (*David White, U. S. Geol. Survey.*)

influenced deposition. Fossils and the general nature of the deposits indicate land origin, as in the case of the overlying red beds, but the limestone in the lower part (which should properly be separated as another formation) is of marine origin. A disconformity occurs at the base of the Supai formation.

Horizontal Strata of the Lower Canyon Walls.—Proceeding still farther downward we reach lower and therefore older beds. First there is a thick, extremely massive blue-gray limestone which forms the most imposing sheer cliffs in the canyon. This formation, known as the Redwall, is stained red by wash from the overlying red beds. The limestone is pure and very uniform in character and contains fossil remains of marine organisms. Its thickness of 500 to 700 feet shows that the sea in which it was deposited covered the region a long time.

Below the Redwall limestone is about 1,000 feet of other horizontally bedded strata, the Tonto beds, which consist of thin-bedded limestone (Muav) above, shale and thin sandstone (Bright Angel) in the middle, and massive coarse sandstone (Tapeats) at the base. All of these rocks

are of marine origin, the different kinds of sediment signifying changing conditions in the sea of this epoch.

The bedding of the Redwall and Tonto strata is parallel and the contact between them is so even in most places that one would not suspect the existence of evidence pointing to a prolonged interruption of sedimentation following the deposition of the Tonto strata. Examination of fossils shows that those of the younger beds are very unlike those of the older, but the significance of this observation is not clear from study of the Grand Canyon region alone. Exposures in some parts of

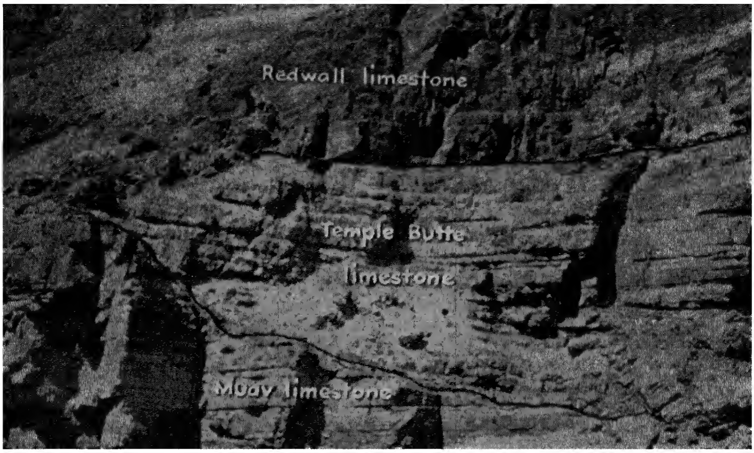


FIG. 17.—A channel-like depression in Muav limestone filled by Temple Butte beds and overlaid by the Redwall limestone. The Redwall rests directly on the Muav formation in most places. Marble Gorge of Grand Canyon. (*R. C. Moore, U. S. Geol. Survey.*)

the canyon show a lenticular formation (Temple Butte) which fills valleys that cut downward at least 100 feet into the upper Tonto beds. Evidently, then, there is a disconformity between the Redwall and the Tonto formations, and locally there are deposits of intermediate age.

Rocks in the Bottom of the Canyon.—The rocks exposed in the bottom part of the Grand Canyon for many miles may be sharply differentiated from the nearly horizontal stratified formations thus far considered. In certain places the canyon bottom consists of regularly stratified rocks, but, unlike those of the upper canyon walls, the beds in the lower series are strongly and rather evenly inclined. Interbedded with sandstone, shale, and limestone, there are igneous sheets of dark-colored intrusive and extrusive rocks. The tilted strata are truncated at the top by a plane of erosion which is nearly horizontal, and on this surface the oldest of the Tonto beds are laid. Where the tilted strata are absent, the Tonto rocks rest on granite, schist, or other crystalline rocks. The contact between the Tonto and these various types of underlying rocks is

very sharp and mostly very even, which shows that the pre-Tonto erosion, of unknown duration, reduced the country to a featureless peneplain. The discordance in geologic structure furnishes basis for designating this break in the sequence of the rocks as an *unconformity* of major importance, which is in contrast to the disconformities at higher levels, where strata in contact at the erosion surface lie parallel.

Algonkian Rocks.—We may first consider the tilted stratified rocks, which are called Algonkian. The total thickness of these rocks is not

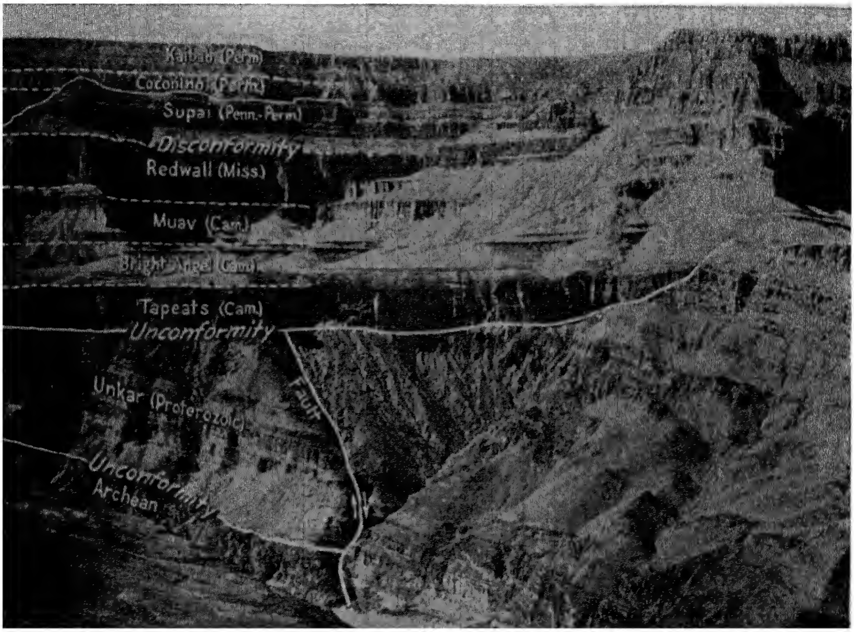


Fig. 18A.—North wall of the Grand Canyon in a part of the Shinumo quadrangle. This view shows remarkably the unconformity at the base of the Tapeats sandstone, the discordance in structural attitude of the beds above and below this unconformity, and the presence of a fault that dislocates the rocks below the unconformity but not those above it.

known, but at least 12,000 feet of beds are exposed locally. The Algonkian strata are obviously older than the Tonto beds, as shown by their position beneath the Tonto. In addition, it is apparent that the tilting of the Algonkian rocks (accompanied or followed by considerable faulting), and the truncation of this great thickness of strata by erosion, took place after the close of Algonkian sedimentation and volcanic activity, and before the beginning of Tonto deposition. The pre-Tonto age of the igneous intrusions and of the faults is shown by the fact that neither the intrusions nor the faults extend above the plane of unconformity. The Algonkian rocks were originally very much more extensive than now, for all but a few remnants were carried away by the pre-Tonto erosion.

This erosion cut deeply into the granitic and associated crystalline rocks that underlie the Algonkian, as shown by the portions of the unconformity at the base of the Tonto that intersect pre-Algonkian granites, schists, and metamorphosed sediments in much of the canyon.

Archean Rocks.—The most ancient rocks exposed in the Grand Canyon consist of metamorphic and coarse-grained igneous rocks of various sorts, chiefly granite. Because of similarity to the complex oldest known rocks of other regions which are termed Archean (begin-

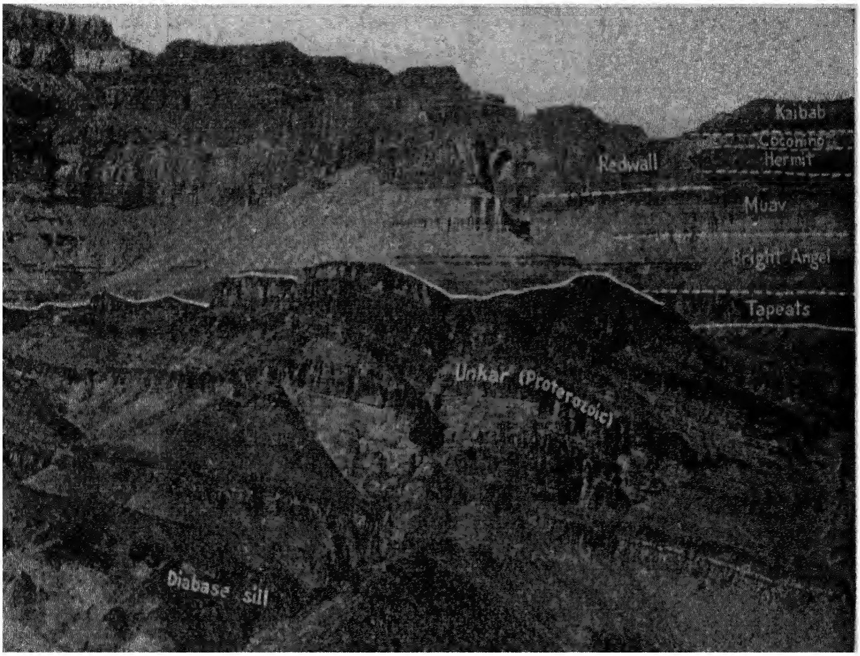


FIG. 18B.—Continuation of the view shown in Fig. 18A. The diabase sill in the lower part of the photograph is traceable for many miles. (*N. W. Carkhuff, U. S. Geol. Survey.*)

ning), the crystallines of the canyon are grouped under this name. These rocks are resistant to erosion and accordingly form a narrow, steep-sided, V-shaped gorge which in places is 1,500 feet deep. Although granite is by no means the only kind of rock in this gorge, nor in some sections even a very prominent kind, the name Granite Gorge is commonly employed. The igneous rocks are intrusive in schist, gneiss, or other igneous or metamorphic rocks. The intrusive masses are necessarily younger than the rocks that they intersect. The thoroughly crystalline nature and prominent cleavage of the metamorphic rocks show evidence of profound compression and heat which have all but obliterated the original characters of the rocks.

That the Granite Gorge rocks belong to a very much older category than the tilted, but otherwise little-altered, sedimentary rocks of the

Algonkian above them is evident from the fact that none of the granitic rocks intrude the Algonkian or higher strata, and from the absence of any significant effects of metamorphic change in the latter. The crystalline rocks have characters that indicate a former position deep within the earth crust. Eventually they were exposed at the surface by erosion of overlying materials. The unconformity at the base of the Algonkian rocks furnishes record of part of this profound erosion. The hard Archean rocks are smoothly beveled; and at the time when the erosion surface was formed, it must have been nearly horizontal. The bedding planes of the Algonkian rocks were also originally horizontal, or nearly so, and the fact that the plane of unconformity at the base of the Algonkian is parallel to the stratification of the overlying strata proves that the erosion plane was approximately horizontal during Algonkian sedimentation. The plane of unconformity has subsequently been tilted in the same manner and to the same angle as that of the overlying strata. It is evident, furthermore, that in places where all of the Algonkian has been eroded, and the plane of unconformity at its base has been obliterated, there is little indication of the true magnitude of the erosion record at the base of the next succeeding (Tonto) beds.

Historical Inferences.—Before leaving our study of the canyon it is desirable to summarize some of the inferences concerning geologic history that have been made and to extend our analysis of certain observations.

Significance of the Order of Succession of Strata.—In the first place, the order of succession or superposition of the strata in the canyon walls certainly indicates the order of their geologic age, the oldest at the bottom and the youngest at the top, for the layers are practically horizontal. They have been elevated vertically some thousands of feet, gently warped, and locally they have been broken by faults or steeply tilted in folds, but the evidence of their relative age is definite and conclusive. The order of changing conditions and events and the sequence of ancient types of plant and animal life on the earth are determined by the order of succession of rock strata. This is a simple but basic observation in the study of earth history.

Significance of the Physical Characters of Rocks.—Next, it is important to know the significance of the different kinds of sediment and of the various physical characters connected with them. Proper interpretation of these things plus determination of their order in time give almost all of the items in the geologic history of one region. If the Grand Canyon district were the only land area in the world, its geologic history would be only very incompletely known, even though we recognize the presence of disconformities and understand that they denote gaps in the record. It would be impossible to determine how great the gaps are, except very roughly, perhaps, by the extent of change in the nature of organisms found in the different beds. There would be no satisfactory basis for evaluating

the time significance of this change. But the Grand Canyon district is not the only place where rock formations are accessible for study. Comparison of this region with others near-by and at a distance is important, because knowledge is added concerning the extent and the uniformity or variability of the different formations. Such comparison indicates, for example, the distribution of the sea at a given time and locates the district we are specially studying in its proper geographic setting. Still more important is the discovery that there are thick formations in some regions that are absent altogether in the Grand Canyon area, the deposits in the other regions corresponding to erosion intervals (disconformities and nonconformities) in the Grand Canyon section.

Significance of the Remains of Life.—The character of plant and animal life that may be preserved in rock strata is obviously important in

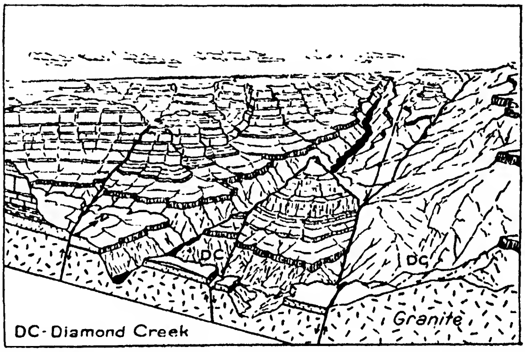


FIG. 19.—Sketch showing north-south trending faults that affect part of the Grand Canyon district. (*R. C. Moore, U. S. Geol. Survey.*)

considering the mode of origin of sedimentary formations and in making other historical inferences. It is commonly possible not only to distinguish marine and nonmarine deposits by this means but to determine the particular environment in the sea or on the land that is represented by the fossils. Indeed, without the evidence afforded by remains of life entombed in the rocks it would be impossible to decipher much of the geologic record.

Significance of Structural Features.—The tilted and faulted attitude of the Algonkian rocks in the bottom portion of the canyon serves to identify an important crustal disturbance that followed the deposition of these rocks and preceded the time of making the Tonto strata. The date of an earth movement can be established as subsequent to the age of the youngest deformed beds, and earlier than the oldest succeeding undisturbed beds.

Correlation of Formations.—The comparison of the sequence of formations (geologic section) in one area with that in another involves the problem of correlation. Equivalence of certain formations in adjacent

areas may be established by their *continuity;* they can be followed or mapped across intervening territory. The Kaibab limestone can be thus traced for hundreds of miles in certain directions, with almost continuous exposures. Where the rocks cannot be followed in this way, *similarity of lithology* and *like sequence of formations* may be especially helpful in determining equivalent beds. One of the most important kinds of evidence in the correlation of sedimentary formations is the comparison of organic remains that are preserved as *fossils* in the rocks, for experience shows that the kinds of fossils in each bed or group of beds constituting a formation are characteristic of that bed or formation and are distinguishable from the fossils of strata at higher or lower levels. By these means, reliable correlation of beds in near-by areas may be established. In regions that are distant from one another, conditions may be unlike. Accordingly, there may be no similarity in the nature of the deposits, but comparison may yet be made on the basis of the fossils. If there was opportunity for intermigration of organisms from one place to the other, identical species may occur in each, notwithstanding intervening distance. If there was no such opportunity for intermigration, the correlations are more difficult and less precise, but general relations are, nevertheless, determinable by comparison of the fossils and in other ways.

In applying these considerations to the Grand Canyon geologic section, attention may be directed again to the "lost interval" (hiatus) between the Tonto and Redwall beds. The magnitude of this break in the record is indicated by the discovery that in certain other regions rocks equivalent to these formations are separated by deposits totaling many thousands of feet and representing at least three major divisions of the geologic time scale. The Tonto formations are thus very much older than the Redwall limestone and overlying beds. The parallel attitude of the bedding planes in the Redwall and Tonto formations indicates that there was no warping or folding of the older rocks preceding deposition of the younger. The even nature of the contact between these formations seems to show that this region was only slightly elevated above sea level during the long interval of nondeposition that followed Tonto time.

The Geologic Column.—The succession of rock formations that is revealed in the walls of the Grand Canyon represents part of the so-called geologic column, which consists of the major and minor divisions of rocks of the earth's crust, arranged according to age. The column is constructed by piecing together the geologic record of many regions that partly duplicate and partly supplement one another. Thus is developed a general geologic time scale, as described in the following chapter. It may be noted here that the Grand Canyon formations belong to the Archeozoic, Proterozoic, and Paleozoic eras of the general time scale, and the rocks of the last-named include the Tonto beds (Cambrian), Temple

Butte limestone (Devonian), Redwall limestone (Mississippian), Supai formation (Pennsylvanian and Permian), Hermit shale, Coconino sandstone, and Kaibab limestone (Permian).

Regional and Special Considerations

We have now examined the nature of the historical testimony that is furnished by physiographic and geologic characters of the Grand Canyon, or, rather, of a part of the canyon that is most readily accessible to the tourist visitor. Before terminating this study, it is desirable to extend our observations to include certain features of the surrounding territory.

Post-Kaibab Formations.—Along the northern and eastern borders of the Grand Canyon plateaus is a thick succession of rock strata that overlie the Kaibab limestone. These younger rocks consist mainly of shale and sandstone and are classed as Mesozoic and Cenozoic. It is unnecessary to describe them here, but it may be said that the geologic history of this region involves the deposition of at least 7,000 feet of beds that have been stripped from the Kaibab-capped plateaus. A few scattered remnants of the post-Kaibab formations, such as those in Cedar Mountain, partly show the former great extent of these younger rocks.

The Grand Canyon Upwarp.—Considered as a whole, the rocks of the Grand Canyon region are not horizontal. They have been pushed

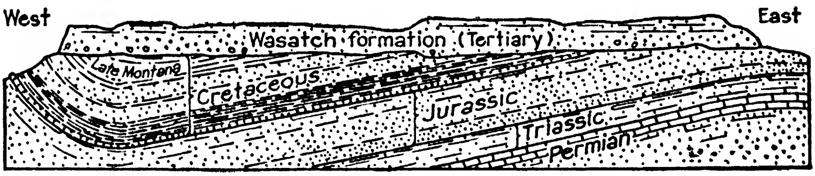


Fig. 20.—Diagrammatic cross-section of rocks at the south edge of Aquarius Plateau, southern Utah. The folding of the pre-Wasatch beds occurred subsequent to deposition of the late Montana (Kaiparowits) strata, which is very long after deposition of the Permian limestone (Kaibab). (*R. C. Moore, U. S. Geol. Survey.*)

upward unevenly, so that the elevation of the top of the Kaibab limestone is several thousands of feet higher in some places than in others. The structure is broadly dome-shaped, but the shape of the dome is asymmetrical and irregular. The rocks dip steeply eastward along the east margin of the Kaibab Plateau, forming what is known as the East Kaibab fold. North-south trending faults with the upthrow on the east intersect the country west of the Kaibab Plateau. Question should be raised as to the geologic date of the folding and faulting, and it is important to learn the methods of answering this query. We must bear in mind that the present structural conditions are not necessarily the result of deformation at any one time; in fact, it is more than likely that different movements have affected the region at different times.

Let us consider first the strongly tilted attitude of the rocks in the East Kaibab fold. The beds are all tilted alike and the youngest forma-

tion that is involved in the folding, as seen in the Grand Canyon district, is the Kaibab limestone. Evidently the time of the folding is post-Kaibab, but we are unable to determine from study here whether the deformation occurred shortly after Kaibab time or very much later. If we follow the East Kaibab fold northward, however, it is found that the Mesozoic beds, which overlie the Kaibab limestone with parallel bedding, are also involved in the folding. This shows that the time of folding was subsequent to the making of these younger formations. Since the thickness of the folded post-Kaibab beds is approximately 6,000 feet, the date of the deformation belongs very long after the deposition of the Kaibab limestone. The age of the youngest strata (Kaiparowits) that are involved in the folding can be ascertained by study of the fossils that

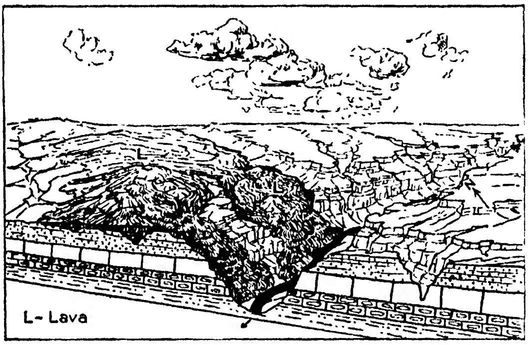


FIG. 21.—Lava flows from vents on the Grand Canyon plateau invade the western part of the canyon. (*R. C. Moore, U. S. Geol. Survey.*)

occur in them. At the border of the High Plateaus in southern Utah, on one part of which Bryce Canyon is located, the tilted Kaiparowits and older formations are seen to be beveled by erosion and overlain unconformably by the capping formation (Wasatch) of the plateaus. The latter beds (of Cenozoic age) are unfolded and are younger than the time of deformation represented by the East Kaibab fold. This serves to determine fairly closely the time of disturbance that we are considering. It is probable that much of the removal of the post-Kaibab strata from the vicinity of the Grand Canyon was accomplished at the time of erosion indicated by the beveling of formations at the plane of unconformity beneath the Wasatch formation.

Studied in a similar manner, it is found that the north-south faults of the Grand Canyon district affect not only the Kaibab and associated rocks but dislocate the Wasatch and still younger formations. The faults are therefore younger than the folding.

Volcanic Activity.—Several volcanic vents are located on the western part of the Grand Canyon plateaus not far from the canyon rim. The lava from some of these flowed over the edge of the canyon, down its walls, and thence for many miles along the canyon bottom. Numerous

remnants of the congealed lava are found. That the invasion of the canyon by the lava flows is a very recent geologic event is shown by the little-altered appearance of the surface of parts of the flows, and by the occurrence of this igneous rock at the bottom of the canyon. The latter fact proves that the canyon had been cut to its present depth at the time of this volcanic activity.

Eruptive igneous rocks that are many hundreds of feet thick occur on the southern Utah plateaus. The approximate age of these can be determined by the observation that they rest on the Wasatch beds, that they are broken by the north-south faults, already mentioned, and that deep canyons have been carved in them. The volcanic activity represented by these rocks is older than that described near the Grand Canyon rim, but the absence of fossil-bearing sediments above the volcanic rocks in southern Utah leaves unsettled the question as to how much older.

SUMMARY

The description of the Grand Canyon formations and analysis of some of their historical implications serve to illustrate the essential methods of approach to study of the geologic record in all accessible parts of the earth. The composition, texture, bedding, degree of uniformity, and geographic extent of rock formations are all significant as to conditions of origin, but evidence of the fossil remains of life is especially important and necessary. The order of superposition of deposits is the essential basis of geologic chronology. The order of succession of rock strata indicates the order of succession of organisms, and this gives fundamental knowledge that may be used in correlating different sedimentary deposits. Nonconformities and disconformities denote gaps in the geologic record, but the time represented by these gaps may be recorded partly or completely elsewhere by sedimentary deposits. Thus, earth history as a whole is built up by patching together the fragmentary records of innumerable geologic sections. Disturbances that modify the earth crust may be dated by determination of the youngest formations affected by the movement, on the one hand, and of the oldest succeeding formations that are unaffected by the movement, on the other. Strata that are deformed are older than the time of deformation, whereas strata of the same region that are undisturbed are presumably younger than the time of deformation. Relations of igneous activity may be ascertained somewhat similarly, but in general less exactly.

CHAPTER V

GEOLOGIC TIME AND ITS DIVISIONS

How old is the earth? What is geologic time and how does it differ from ordinary time as expressed in years or centuries? Is geologic time accurately measurable? Can it be divided into unit parts and, if so, what are these and how are they differentiated?

The first of these questions engaged the attention of ancient thinkers among Chaldeans, Egyptians, Greeks, and Romans. It interested a few of the none too numerous men of learning in the Middle Ages and very early modern times. In 1650, Bishop Ussher of Ireland gave out a chronology of Biblical events in which the beginning of the world was assigned to the year 4004 B.C. The sanction of churchmen and the inclusion of this chronology in various publications of the Scriptures led to wide acceptance in the eighteenth and early nineteenth centuries of Ussher's dictum as to the age of the earth. And the absurdity is not completely buried even at the present day!

Evidence derived from the earth itself was rightly interpreted by some of the ancient writers as indicating that the age of our planet is numbered in very many thousands of years. The beginning of geology as a science, which may be placed at less than 200 years ago, led gradually to rational attempts to measure geologic time and to determine its major divisions. It has become apparent that the age of the earth and also the duration of some of the natural divisions of geologic time are numbered in very many millions of years. These subjects are properly introduced at this point in our study of earth history.

MEASUREMENT OF GEOLOGIC TIME

Geologic time may possibly be measured by observation of the results of some process that has operated steadily upon or within the earth. The hourglass is a comparable means of measuring time, for the rate of fall of sand grains through the tiny aperture of the glass is constant and the amount of fallen sand at a given instant is directly proportional to the lapse of time since the measurement was begun. So, if accumulation of sand and other sediments by natural agencies to form stratified rock takes place at a certain constant rate, and if the total amount of sedimentary rocks and the rate of deposition are known, the time represented by the making of the rocks may be computed. Determinations of the age of the earth on the basis of the thickness of stratified rocks have been undertaken, but they are not very reliable. The conclusions are uncertain

because the rates of sedimentation differ greatly for different kinds of sediments, because these rates are not exactly known, and because they are evidently not constant even for rocks of the same composition. Also, measurements of the total thickness of sedimentary rocks are inaccurate, and no satisfactory account can be taken of the time represented by interruptions of sedimentation (disconformities and nonconformities). It is of interest, nevertheless, that even this crude and incomplete means of measuring geologic time indicates that the earth is scores of millions of years old.

Measurement Based on Salt in the Sea.—Large quantities of mineral substances are carried in solution to the sea. Some of these are precipitated but others, such as common salt, remain mostly in solution and accumulate in the ocean. Accordingly, if the rate of addition of salt to the sea is measured, if it is constant, and if the total amount of oceanic salt is determined, we can compute the time required to supply the salt. Investigations along this line give a figure amounting to about one hundred million years. But here again there are uncertainties and inaccuracies. The rate of addition of salt to the sea has certainly changed greatly during geologic time, depending on the size and elevation of the continents, on fluctuations of volcanic activity which brings chlorine and water vapor to the atmosphere, and on other conditions. Enormous quantities of salt have been precipitated from sea water to form salt beds. Altogether, this method of measuring the age of the oceans is only very approximate, and it must be noted that the age of the oceans is not equivalent to the age of the earth as a whole.

Measurement Based on Radioactive Disintegration.—In recent years it has been learned that certain elements of complex atomic structure, such as uranium and thorium, are constantly undergoing a spontaneous disintegration which produces radium. The radium breaks down to form end products consisting of the gas helium and a heavy metal that is indistinguishable from ordinary lead except by a very slight difference in atomic weight. Careful observations have determined the rate of this disintegration, and it appears that the rate is entirely unaffected by any changes in the physical environment of the minerals. Accordingly, analysis of any strongly radioactive mineral sample makes possible the direct computation of its age, for with knowledge of the constant rate of disintegration it is merely necessary to determine the quantities of remaining unaltered uranium or thorium and one or other of the decomposition end products. Some of the helium is likely to escape and it is harder to measure accurately than the lead, so the lead-uranium ratio is commonly sought. There are difficulties in actual work which have led to some discrepancies in results. For example, weathered samples give erroneous figures because some of the minerals may be lost; or if primary lead is present, it may be confused and combined with radioactively

formed lead. Also, since the rates of disintegration of uranium and thorium are different, mixtures of these in a sample must be separately determined. Nevertheless, a rapidly growing body of fairly accordant data indicates the value of this method of measuring geologic time. It is subject to the limitation that specimens on which reliable age deter-

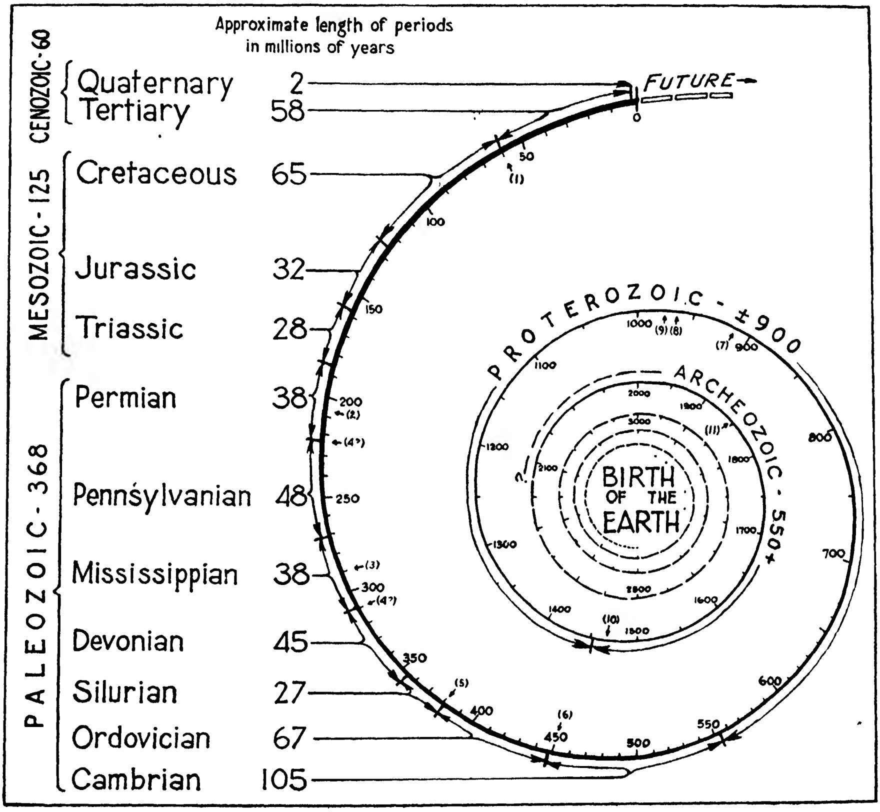


FIG. 22.—Diagram representing the length of geologic periods and eras.

The figures here given are based mainly on age determinations of radioactive minerals (*Kovarik and Holmes*), supplemented by data on comparative thickness of systems, estimated rates of sedimentation, and time values of unconformities (*Schuchert*). The spiral type of diagram modified from David White.

The most reliable age determinations of radioactive minerals (shown by small index numbers on the diagram) are as follows: (1) *Earliest Cenozoic*, 60 million years; (2) *Early Permian*, 207 (?) million years; (3) *Mid-Devonian*, 290 million years; (4) *Devonian or Carboniferous*, 224 to 310 million years; (5) *Late Ordovician* (?), 380 million years; (6) *Latest Cambrian*, 450 million years; (7) *pre-Cambrian* (Norway), 913 million years; (8) *pre-Cambrian* (Norway), 966 million years; (9) *pre-Cambrian* (Norway), 975 million years; (10) *pre-Cambrian* (South Dakota), 1,465 million years; (11) *pre-Cambrian* (Russia), 1,852 million years.

minations can be based are of igneous origin, and the age of associated sedimentary formations must be ascertained indirectly.

The Age of the Earth.—Samples of radioactive minerals from some of the oldest rocks known at the earth's surface have been computed to be 1,850 million years old; even higher figures have been obtained. These ancient rocks at the earth's surface are surely much younger than

the beginning of the earth. According to the molten-earth hypothesis, the time from the beginning of the planet to the making of the oldest surface rocks whose age has been measured may be estimated roughly at 500 million years; this would make the total age of the earth more than 2 billion years. According to the solid-earth hypothesis, which calls for slow building of small planetesimals, it is possible that the time from the beginning of the earth to the making of the oldest known surface rocks may be 2 billion years or more, making the total age of the earth 3½ billion to perhaps 5 billion years. It is evident that the time represented by earliest earth history, as discussed in Chap. III, is little more than a guess.

SUBDIVISION OF GEOLOGIC TIME

The chronology of earth history is not established in terms of years but is based rather on the sequence and characters of the rocks. It is known that the deposition of each group of rock strata represents a time which may range from many hundreds or thousands of years to millions; also, it is evident that intervals of erosion marked by unconformities represent much time. The foundation of the geologic time scale is the succession of sedimentary deposits which are divided by interruptions of sedimentation. The times of accumulation of sediment are like the chapters of a book, and the breaks due to nondeposition mark the divisions between the chapters. Smaller parts of the geologic section may be compared to paragraphs. We recognize a few especially important lines of division in the rock succession which denote major partitions of geologic time, and these suggest separate volumes. Another and perhaps better comparison is the succession of reigns in a monarchy. One reign is longer than another and each may be marked by various distinguishing characters; the geologic time divisions of first rank may be compared to changes of dynasties. In geologic history, however, there is a gap in the record between most successive "reigns."

Basis of the Geologic Time Scale.—The first attempts, more than a century ago, to classify the rocks of the earth from the standpoint of age or origin led to a twofold division: *Primary*, for the granites, schists, slates, and unfossiliferous rocks, some of which were thought possibly to represent the original crust of the earth, and *Secondary*, for the great series of fossiliferous strata resting on the Primary. The geologic time represented in the making of these rocks was accordingly divided into two great parts. Later, the units *Tertiary* and *Quaternary* were added to include comparatively recent, largely unconsolidated sediments, but the time of both of these together is much less than that of either of the first two divisions. The term Primary is now replaced by Archeozoic and Proterozoic, the so-called "Transition" between Primary and Secondary is largely equivalent to what is now called Paleozoic, and the Secondary is

represented by the Mesozoic. The names Tertiary and Quaternary are still employed.

After it became realized that the shells, bones, and impressions of leaves found in stratified rocks were actual remains of life that had existed on the earth at the time the rocks were formed, the most important observation bearing on age classification of the rocks was the discovery that the fossils of each layer or group of layers were characteristic of that horizon, and that they differed from fossils in beds above and below. William Smith of England is credited with first pronouncement of this fact in about the year 1800. Here was a real basis for geologic chronology. However, it was long believed that the life represented in each formation was a separate creation, wholly independent of what had gone before. Destruction of existing life by an assumed general catastrophe was followed by creation of the slightly different organisms found in the next younger beds. The fact that the rock layers and their contained fossils are separable into many distinct, easily recognizable units shows that geologic time may be subdivided on the basis of the deposits and the organic remains in them, but ideas have entirely changed concerning the hypothetical catastrophes and supposed new creations. The principle of the uniform operation of nature's laws, sometimes called *uniformitarianism,* has now long been accepted as a guide in study of the geologic record, and it does not accord with catastrophism in either the inorganic or the organic world. There is evidence of repeated changes in conditions of erosion and deposition, of advances and retreats of the seas, of alterations of environment that affect life, but these changes are continuous and gradual. The geologic time scale is based on the record of these conditions, both inorganic and organic.

Units of the Time Scale.—The largest division of the geologic time scale is called an *era.* Each era contains a number of *periods,* and the periods are divided into *epochs;* the epochs may be subdivided into *ages,* and these into *stages* and *substages.* The nomenclature of time divisions and the corresponding rock terms, as used in America, are shown in the following table.

Divisions of the Geologic Time Scale and Corresponding Rock Terms

Rank	Time terms	Rock terms
1	Era	Sequence[1]
2	Period	System
3	Epoch	Series
4	Age	Group
5	Stage	Formation
6	Substage	Member

[1] No designation for the rocks of an era is in common use. The term "sequence" will be used in this book.

The word *eon* may be used for an extremely and indefinitely long time, but it is not employed commonly in geology.

Eras.—The largest division of the time scale is the era. The eras are defined by unusually pronounced and widespread interruptions in sedimentation and by accompanying apparently sudden and great changes in the nature of life. The "critical periods" or revolutions that serve to mark off one era from the next are more or less prolonged intervals when there was maximum physical change. This change involves unusual diastrophism, which is commonly marked by elevation of great mountain ranges in different parts of the globe and by a general highly emergent condition of the continents. Naturally there is an important accompanying biologic reorganization. The era includes the enormously long time between such major breaks in the geologic record.

Periods.—The era contains smaller time units called periods, which are defined in exactly the same manner except that the times of crustal movement at the beginning and end are less pronounced, and accompanying interruption of sedimentation and changes in character of organisms are smaller. Ideally, a geologic period begins with a general emergent condition of the continents, the seas being accordingly restricted; as time elapses, the lands are slowly worn down and the sea advances over the continents, maximum submergence occurring toward the middle or in the latter part of the period; renewal of diastrophic movements rejuvenates the lands and causes a retreat of the seas, bringing the period to a close. These geographic changes exert a marked effect on organisms of the sea and land. A period of time is long and the thickness of rocks formed is generally great.

Epochs and Ages.—A period may be divided into epochs and ages depending on the existence of minor but important changes in conditions during the period. Thus, the lesser advances and retreats of the continental seas, separated by erosion breaks of relatively short time value, may be distinguished. Also, the successive transgressions of seas from different oceanic basins, containing dissimilar shallow-water organisms may be regarded as marking separate epochs. Times of deposition of different sorts of sediment or times marked by slight but significant changes in the character of fossil organisms may be distinguished as individual ages.

Names of the Time Divisions

The names applied to divisions of the geologic time scale are the result of long and slow development. They are an outgrowth of the work of many individuals in many regions. There is yet lack of uniformity in certain respects, especially in different continents, but the variations are mainly in the nomenclature of units smaller than the periods.

Names of the Eras.—The designation of the eras which is almost universally accepted, is based on the ending -zoic (from the Greek) referring to life. Thus, *Archeozoic* means "beginning of life"; *Proterozoic*, "very early life"; *Paleozoic*, "ancient life"; *Mesozoic*, "medieval life"; and *Cenozoic*, "recent life." These names suggest the grand stages in the evolution of life which constitute a most interesting part of earth history. The first two of the era names given are less generally used than the others because actual evidence of life in these very ancient rocks is small and the names based on life are partly theoretical. The term *Psychozoic*, "soul or mind life," has been introduced by a few geologists to apply to Recent time, but there is little real reason for such a division.

Names of the Periods.—The names of the periods are mainly drawn from European sources because of the early work done on that continent. They are only partly based on geographic features.

Periods of the Paleozoic Era.—Among rocks now assigned to the Paleozoic era the coal-bearing formations, of great economic importance, were grouped together at a very early date under the term *Carboniferous* (coal- or carbon-bearing). Beneath these strata in much of Great Britain and northern Europe there is a prominent thick reddish sandstone, lacking in marine fossils, which came to be known as the Old Red sandstone, to distinguish it from a somewhat similar deposit above the Carboniferous rocks that was named the New Red sandstone.

Stratified rocks beneath the Old Red sandstone were at first classified simply as part of the "primitive series," but it was later recognized that here is a thick succession of marine strata some of which are highly fossiliferous. Investigations of these carried on mainly by the Englishmen Adam Sedgwick and Sir Roderick Murchison led to the designation of a lower system called *Cambrian* (Latin for Wales, where the beds are well exposed) and of an upper system called *Silurian*, (after the Silures, a Celtic tribe that once inhabited the portion of western England and eastern Wales where these rocks occur). A division of the Silurian into two parts, upper and lower, was recognized by Murchison. Subsequently, it became apparent that the Upper Cambrian defined by Sedgwick was essentially the same as Murchison's Lower Silurian. The name Cambrian is now restricted to the formations (Sedgwick's Lower Cambrian) below this intermediate series which was long a subject of controversy as to classification and nomenclature. In Europe, some geologists, mostly those on the continent, still employ the terms Lower and Upper Silurian in Murchison's sense, and this usage was followed in early American works. Since 1879, however, the name *Ordovician* has generally come to be applied to the "Lower Silurian" of Murchison, and the term Silurian is restricted to his "Upper Silurian."

The discovery in southwestern England of marine fossils apparently intermediate in character between those known from the Silurian and

DIVISIONS OF GEOLOGIC TIME

Eras	Periods	Epochs: North America	Epochs: Europe	Life and other characters	Crustal Movements	Dominant life Characters	
CENOZOIC	Quaternary	Recent	Recent	Dominance of man		Age of Mammals	Age of Modern Seed Plants (Angiosperms)
		Pleistocene	Pleistocene	Periodic glaciations Extinction of large mammals	Cascadian revolution		
	Tertiary	Pliocene	Pliocene	Beginning of man			
		Miocene	Miocene	Culmination of mammals			
		Oligocene	Oligocene	Culmination and extinction of archaic mammals			
		Eocene	Eocene	Rise of mammals and modern floras			
MESOZOIC	Cretaceous	Upper: Lance	Danian	Last of dinosaurs pterodactyls, large marine reptiles and toothed birds Last of ammonites Rise of flowering plants and modern insects Widespread deposition of chalk	Laramide revolution	Age of Reptiles and Ammonites	
		Upper: Montana	Maestrichtian (Senonian)				
			Campanian (Senonian)				
		Upper: Colorado	Santonian (Senonian)				
			Coniacian (Senonian)				
			Turonian				
		Upper: Dakota	Cenomanian				
		Lower: Comanche	Albian				
			Aptian				
		Lower: (Absent)	Barremian				
			Neocomian				
	Jurassic	Upper	Portlandian	Rise of toothed birds Culmination of ammonites Prolific marine fauna	Jurasside disturbance		Age of Ancient Seed Plants (Gymnosperms)
			Kimmeridgian				
			Lusitanian				
			Oxfordian				
			Callovian				
		Middle	Bathonian				
			Bajocian				
		Lower	Lias				
	Triassic	Upper	Rhaetic	Rise of dinosaurs pterodactyls marine reptiles Rise of ammonites Rise of cycad like plants	Palisade disturbance		
			Keuper				
		Middle	Muschelkalk				
		Lower	Bunter				
PALEOZOIC	Permian	Upper	Zechstein	Rise of primitive reptiles Last of trilobites Glaciation extensive salt beds	Appalachian revolution	Age of Amphibians	
		Lower	Rotliegende				
	Pennsylvanian	Virgil	Stephanian (Carboniferous)	Great coal making period Spread of amphibians Culmination of spore-bearing plants			Age of Spore-bearing Plants
		Missouri					
		Des Moines	Westphalian (Carboniferous)				
		Morrow	Namurian (Carboniferous)		Culmide disturbance		
	Mississippian	Chester	Dinantian or Culm (Carboniferous)	Culmination of crinoids Abundant sharks			
		Valmeyer					
		Kinderhook					
	Devonian	Upper: Chautauquan	Famennian	Rise of fishes Rise of land plants, first forests	Acadian disturbance	Age of Fishes	
		Upper: Senecan	Frasnian				
		Middle: Erian	Givetian				
		Middle: Ulsterian	Eifelian				
		Lower: Oriskanian	Coblenzian				
		Lower: Helderbergian	Gedinnian				
	Silurian	Cayugan	Downtonian	Abundant brachiopods reefcorals Salt deposits and iron ore beds	Caledonian revolution	Age of Invertebrates	Age of Sea-weeds
			Ludlovian				
		Niagaran	Wenlockian				
		Medinan	Llandoverian				
	Ordovician	Cincinnatian	Caradocian	Culmination of trilobites First appearance of fish like vertebrates	Taconic disturbance		
		Mohawkian					
		Chazyan	Llandeilian				
		Canadian	Arenigian				
	Cambrian	Ozarkian	Tremadocian	Dominance of trilobites Rise of primitive cephalopod First abundant invertebrate fossils	Green Mtns disturbance		
		St Croixian					
		Acadian					
		Waucoban					
PROTEROZOIC	Keweenawan			Remains of life mostly lacking Fossil algae Iron and copper deposits	Killarney revolution	Rise of Invertebrates	
	Huronian	Upper (Animikian)					
		Middle					
		Lower			Algoman disturbance		
	Timiskamingian						
ARCHEOZOIC	Keewatin		Archean	Granitic and schistose rocks complex structure Only indirect evidence of existence of life	Laurentian revolution		

Carboniferous led Murchison and Sedgwick to the conclusion that the containing strata correspond in age to the nonmarine Old Red sandstone which elsewhere comes between Silurian and Carboniferous. In 1839, they introduced the name *Devonian* (from the county Devonshire in which the marine strata were found) as designation for the geologic period following the Silurian and preceding the Carboniferous. Though the deposits selected as the type are very ill adapted to serve as a standard for comparison with beds of this age in other regions, the name has come into general use.

Studies in Europe, North America, and other parts of the world have shown that the rocks of post-Devonian age are clearly divisible into at least two or probably three systems that are generally separated by widespread unconformities. In Europe these are designated from oldest to youngest, respectively: (1) Lower Carboniferous, Culm, or Dinantian, (2) Upper Carboniferous or Coal Measures, and (3) Permian. In North America the corresponding terms in common use are (1) *Mississippian*, (2) *Pennsylvanian*, and (3) *Permian*, but the differentiation of the last two is dependent on paleontologic comparison with deposits in the Old World.

Periods of the Mesozoic Era.—The lower part of the "Secondary" or Mesozoic rocks early came to be known as *Triassic* (threefold) because of the three prominent contrasting kinds of strata that are widespread at this horizon in Germany and adjacent areas. The second period is named *Jurassic* on account of extensive exposures in the region of the Jura Mountains in eastern France, Switzerland, and southwestern Germany. The upper part of the Mesozoic is especially characterized by beds of chalk and accordingly acquired the name *Cretaceous* (Latin *creta*, meaning chalk).

Periods of the Cenozoic Era.—Origin of the Cenozoic period names *Tertiary* and *Quaternary* has already been noted. The subdivisions of these are rather artificial and poorly conceived terms based on the proportion of living to extinct species of organisms found as fossils in the rocks. Thus Eocene (dawn of recent), Oligocene (little recent), Miocene (half recent), Pliocene (more recent), and Pleistocene (most recent) indicate the gradual approach in biologic characters to the present geologic epoch called Recent.

The accompanying table of the geologic time scale is introduced for the purpose of reference and to show in concise form the subdivisions that are generally employed in America and Europe. The youngest divisions of time are arranged at the top and the oldest at the bottom, as the rocks of corresponding ages occur in nature.

SUMMARY

Geologic time can be measured with varying accuracy by determination of the accumulated results of processes working at a known rate

throughout the time to be measured. The most reliable method is based on study of the disintegration of radioactive minerals, which indicates that some ancient rocks at the earth's surface are more than 1,850 million years old. The age of the earth may be estimated at 2 to 5 billion years.

Subdivision of geologic time is based on the sequence and character of the rock formations, and especially on the occurrence of unconformities and crustal disturbances of varying importance. The time division of first order, called era, extends from one of the most important "breaks" or times of critical change in physical and biologic conditions to the next one. The divisions of successive lower rank, period, epoch, age, and stage, are based on lesser interruptions and changes shown in the geologic record.

The names of the eras denote stages in the general development of life. The period names are derived mostly from Europe where the rocks were first studied carefully.

THE PRE-CAMBRIAN ERAS

CHAPTER VI

THE OLDEST KNOWN ROCKS

The part of earth history that is decipherable from study of rocks at the earth's surface properly begins with the very oldest rocks known. Inferences concerning ancient conditions and events on the earth that may be drawn from the nature and structure of these rocks are much more definite than those concerning the origin and earliest history of the globe.

But how can these oldest rocks be recognized? In the Grand Canyon region we have noted that each rock layer in downward sequence is older than those above, and that the rocks in the lowest part of the canyon beneath the great unconformity are the oldest in this region. Determining relative age by order of superposition, one might say that the bottommost rocks in the thickest discoverable series of rock layers should be the oldest. Except in the case of intrusive igneous rocks, which are dated geologically from the time of their solidification, and which, accordingly, are always younger than the rocks they invade, identification of oldest exposed rocks in any one region in this manner is correct. But this does not necessarily identify the most ancient rocks in the world, for the reason that the selected very thick series of superposed beds may all represent deposits of comparatively recent geologic times. Illustration is afforded by areas in California where exposures of stratified rocks totaling more than 50,000 feet in thickness rest on ancient-looking crystalline rocks, yet the latter are known to be as young as Jurassic. Quest for the oldest rocks, therefore, is not simply based on local order of superposition. We must first take account of information concerning age that is given by fossils and start search from the lowest obtainable geologic datum as distinguished by fossils. Such a datum is found in the very widespread plane of unconformity which occurs in all parts of the world beneath the lowest Cambrian sediments.

THE SUB-CAMBRIAN UNCONFORMITY

Cambrian strata, which are the lowest and oldest containing abundant animal remains, can be identified readily by the nature of their fossils. Practically everywhere, as far as known, the Cambrian rests unconformably on older rocks which may consist likewise of sediments, of granite or other igneous rocks, or of highly metamorphosed rocks. The

difference between Cambrian and pre-Cambrian rocks in degree of metamorphism is generally very striking. The pre-Cambrian rock surface in most places was carved by erosion to a comparatively smooth plain before the Cambrian sediments were deposited. This is clearly shown in the Grand Canyon. Where the rocks below the unconformity are granite, gneiss, schist, or similar deep-seated crystalline materials, it is evident that this erosion must have removed many hundreds of feet of the previously existing earth crust, because coarse-grained intrusive igneous rocks and considerably metamorphosed rocks are not formed at the surface or even at very shallow depths. The extremely widespread

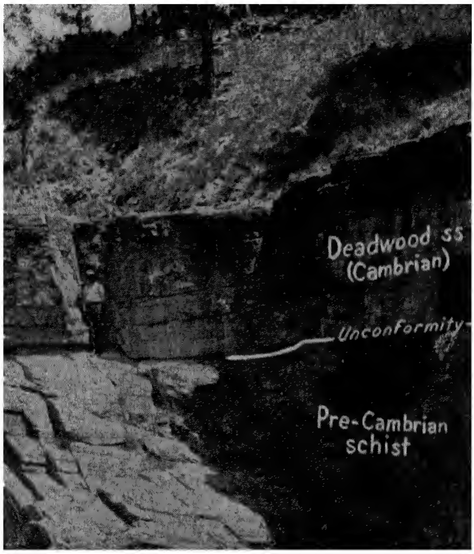


Fig. 23.—An exposure of the sub-Cambrian unconformity in the Black Hills region, South Dakota. Cambrian sandstone rests on a smooth erosion surface cut on pre-Cambrian schist. (*N. H. Darton, U. S. Geol. Survey.*)

nature of the unconformity and the deep-seated character of the pre-Paleozoic rocks in so many places furnish basis for the conclusion that most of the continental areas, where observations are possible, must have been considerably elevated above the seas for a long time. The land surface not only was cut downward deeply but it was well smoothed.

Where are the sediments that were derived from the lands during this erosion? Their aggregate volume must be enormous, yet we know almost nothing about them. Presumably they were transported to areas beyond the borders of the continents, where they are now concealed. Some of the sediments belonging to very late pre-Cambrian time appear to have been deposited in broad depressions of the land, eventually filling them so that the aggraded surface was made even with the

surrounding plain of denudation. However this may be, there is certainly a great "lost interval" in the geologic record at the base of the Cambrian.

The old erosion surface, gently warped but nearly flat-lying, may be seen on the flanks of the Adirondacks in northeastern New York, along the edge of the Cambrian in north central Wisconsin, around the Black Hills in South Dakota, in the Grand Canyon, and in many other places. Tilted upward so that it now stands very steeply inclined or even tipped beyond the vertical, it is found in the Appalachian Mountains, bordering the Front Range of the Rockies, and elsewhere.

This unconformity defines a major datum in geologic history which is analogous to that of the birth of Christ in reckoning dates of European and American history. The pre-Cambrian rocks thus represent time

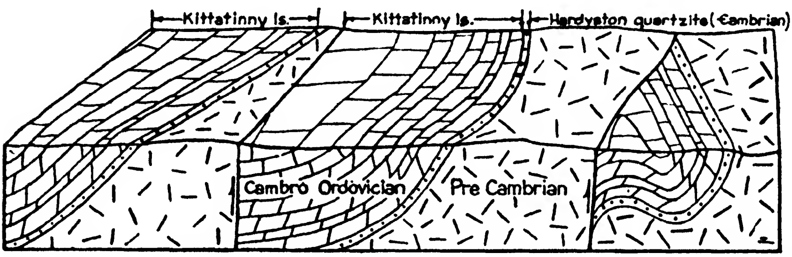


FIG. 24.—Block diagram of a part of the Franklin Furnace quadrangle, New Jersey, showing relations of pre-Cambrian and Cambrian rocks.

The Hardyston quartzite was deposited as horizontal layers of sand and, together with other rocks of the region, has been folded and faulted subsequently. Because the sand was originally horizontal, the surface on which it rests must also have been horizontal, and the sub-Cambrian unconformity thus defines a peneplain which is now greatly deformed.

which in this comparison corresponds to years before Christ in human history. The quest for the most ancient surface rocks begins at the sub-Cambrian plane of unconformity and proceeds downward.

DEVELOPMENT OF KNOWLEDGE CONCERNING THE OLDEST ROCKS

Work of Logan.—The earliest successful attempt at subdivision and differentiation of the pre-Cambrian rocks may be credited to Sir William Logan, first director of the Geological Survey of Canada, who made observations along the north side of the St. Lawrence in 1843 and following years and later extended his investigations to the country north of Lake Huron. The granite and its metamorphosed gneissic equivalents in the St. Lawrence region he named the *Laurentian*. Discovery of a series of slates, quartzites, and conglomerates, the last containing pebbles and boulders of granite and gneiss, led to recognition of a very important system of rocks younger than the Laurentian, since these sediments rest on the massive crystalline rocks and contain material derived from them. These sediments are typically developed in the country northeast of Lake Huron, on account of which they were named *Huronian*. Finally, still another series of pre-Cambrian rocks younger

than Huronian was distinguished by Logan. This is the copper-bearing series that rests unconformably on the Huronian; it is now known as *Keweenawan.* At least three major divisions of the pre-Cambrian of the Canadian area were thus differentiated by Logan. Because of the importance of his pioneer work leading toward a true understanding of the complex geology of these old rocks, Logan is sometimes called the "father of pre-Cambrian geology."

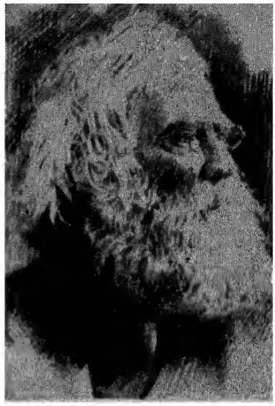


FIG. 25.—Sir William Logan (1798-1875).

Later Investigations.—Subsequent studies, especially by geologists of the Canadian Survey (Adams, Barlow, Bell, Coleman, Collins, Dawson, Quirke, and many others) have extended knowledge very greatly in the region first examined by Logan. There are many complexities and puzzling problems that are not yet solved but the order of succession of many rock divisions is now known definitely. The country south of Lake Superior has been studied intensively in many places because of rich deposits of iron and copper. Much important information concerning the very ancient rocks and their geologic history has been gathered, particularly through the work of Irving, Van Hise, and Leith of the United States Geological Survey.

METHODS OF CLASSIFICATION AND CORRELATION

In classifying the pre-Cambrian rocks according to age and in correlating formations of one region with another, dependence must be placed entirely on physical characters of the rocks, for fossils of any sort are exceedingly rare or absent altogether. Observations of the following are most significant: (1) composition, texture, and general lithologic character of the rocks, (2) order of superposition or sequence, including time of igneous activity, especially of plutonic intrusions, (3) structure, especially as related to general crustal movements, and (4) major or minor unconformities. In addition, (5) computation of geologic age by measurement of the disintegration products of radioactive minerals in the pre-Cambrian rocks is being undertaken and may prove valuable.

Lithologic Character.—Differentiation of the pre-Cambrian rocks according to age first requires separation of the igneous, metamorphic, and sedimentary rocks, and under each of these classes recognition of the different main types is necessary. Schist or other metamorphosed rock is almost surely older than unaltered sedimentary or igneous rocks of the same area, for the forces of metamorphism which produced the schist should otherwise have affected all. Consideration must be given, however, to differing strength of the various kinds of rocks, since

shaly beds, for example, are much more readily deformed than massive quartzite. In correlating the rocks of different regions, comparison should first be made of the kinds of rock that are present in each. Formations of the same type, especially if they contain distinctive peculiarities of mineral composition, texture, and other features, are more likely to be equivalent than unlike formations. Thus, certain Proterozoic iron and dolomite formations may be recognized and correlated,

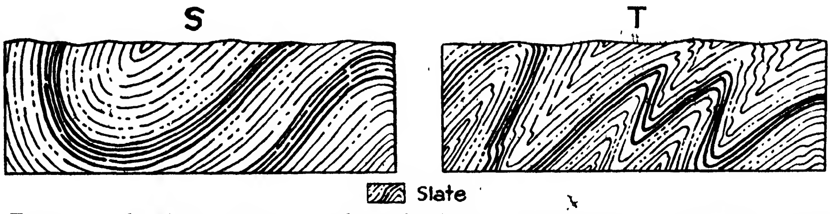


FIG. 26.—The *similar lithology* of the rocks shown in sections *S* and *T* suggests possible equivalence of these rocks, but it is also quite possible that the age of one is altogether different from that of the other.

but even these correlations may not safely be extended to distant regions.

Order of Sequence.—The order of sequence in stratified rocks is determined by superpositon of the rock layers. This is most simple in undisturbed or slightly folded strata, but in parts of the pre-Cambrian areas the strata may be vertical, overturned, or highly contorted. Occasionally, recourse may be had to such features as cross-bedding, ripple marks, and peculiarities of jointing, in determining the order of

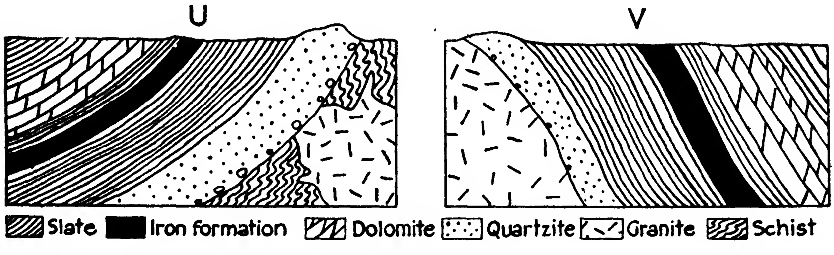


FIG. 27.—The *like sequence* of lithologic types shown in sections *U* and *V*, which occur a number of miles apart but in the same region, affords much stronger basis for correlation of the rock formations represented than for those shown in Fig. 26. These sections also show *similar structure* and a like relation to a prominent *unconformity*.

sequence, but these are seldom recognizable where the rocks are highly disturbed. Sedimentary or volcanic rocks in contact with deep-seated igneous rocks may be recognized as younger (except in certain cases of faulting) if they show no local metamorphic effects from the igneous mass, and especially if they contain pebbles or cobbles derived from the igneous rock; and they may be recognized as older if the intrusive igneous rock cuts through or across them and has altered them.

Structure.—In a general way the structure of the pre-Cambrian rocks is significant as regards age, the younger, which have been subjected to fewer crustal disturbances, being less folded and faulted, and the older, which have been subjected to greater deformation, being more complex in structure. This is shown in the Grand Canyon region where the Algonkian rocks are merely tilted and faulted, but the Archean rocks are very complex in structure. It is also shown in various parts of Canada, but the fact that rocks of a given age may be little disturbed in one region and profoundly altered in another adds greatly to difficulties. Similarity of structure is not of itself a reliable basis of correlation.

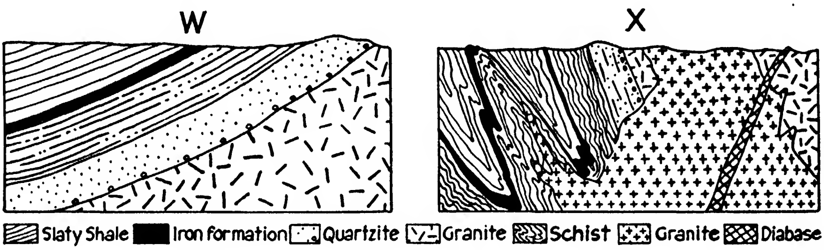


FIG. 28.—The dissimilar *structure* of the rocks in sections *W* and *X* suggests that those of *W* are younger than the formations of *X*, but this is a very unsafe assumption. The sedimentary rocks of the two sections are actually equivalent in age.

Unconformities.—Unconformities represent erosion intervals which interrupt the sequence of sedimentary deposition and follow crustal disturbances that elevate the land. Determination of age relations is based partly on the rocks which are eroded, or truncated by the erosion, but more on the deposits which subsequently are laid down above the plane of unconformity.

Radioactive Determinations.—Radioactive minerals occur in some of the pre-Cambrian igneous rocks. When amounts of these sufficient for accurate measurement of their disintegration products are found, there is a basis not only for computation of the geologic age of the minerals and containing rocks but for comparison and correlation of rocks in widely separated areas. Thus, a series of determinations on specimens from pre-Cambrian rocks in different parts of Ontario shows one group in which the computed age ranges from 1,138 to 1,296 million years, another coinciding at about 869 million years, and others still younger (Ellsworth, 1930). Concordant results give promise to this method of investigation but it has not reached a state where it can be used as an aid in mapping.

All together, these criteria afford basis for fairly definite determination of the time sequence of pre-Cambrian rocks in various regions and for comparison of the rocks in different areas. Difficulties lie mainly in the complexity of structure and extreme metamorphism of certain districts, in regional variation of lithologic characters, and to a large extent in

lack of exposures. Considering the vastness of the pre-Cambrian areas, however, and the very detailed study of them which is necessary, it may be said that exploration has only started.

DIVISIONS OF THE PRE-CAMBRIAN

The pre-Cambrian rocks may be divided readily into two main parts, of which (1) the younger is dominantly composed of sedimentary rocks which in most but not all places have moderately simple structure and which in general show clearly the order of succession, and (2) an older part distinguished by dominance of extreme alteration by metamorphism, prevalence of deep-seated igneous and metamorphic rocks, and very great complexity of structure which is characteristic of rocks of the deep zone. It is significant that this division which appears so clearly in many parts of North America is equally well observed in other parts of the world.

Proterozoic and Archeozoic.—The eras of time which are represented by the two main parts are termed respectively the Proterozoic and Archeozoic. The Proterozoic sequence consists of several systems with a long and complex history. It is younger than the Archeozoic because it uniformly overlies the latter unconformably. The Archeozoic is made up broadly of two types of rock: (1) crystalline schists that are highly metamorphosed sediments and igneous rocks, and (2) granites that in places are changed to gneisses. The first group includes also large masses of nonschistose lava flows and other rocks in some regions.

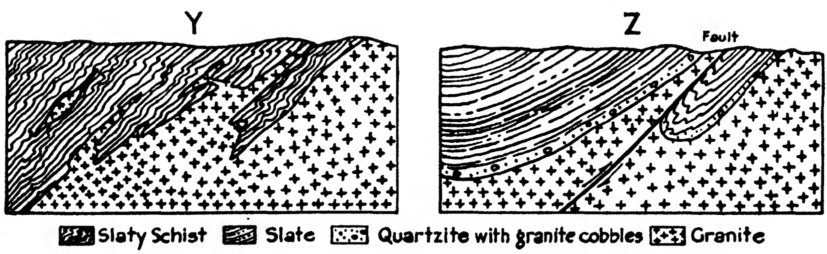


FIG. 29.—Section *Y* shows granite in contact with slaty schist. Dikes of granite invade the schist. Section *Z* shows similar granite in contact with a quartzite containing granite cobbles, overlaid by slate. What is the relative age of the granite and slaty rocks in these cases?

The Oldest Known Rocks.—At one time the granites of the Archeozoic sequence were regarded as parts of the original molten crust of the earth, the schists being metamorphosed sediments and volcanics resting on the igneous rocks of the supposed crust. Closer observation, however, has shown that in every case the granites cut across lamination planes of the schists, that dike or veinlike masses of granite project into the schists, and that the schists have been altered in the vicinity of the contact. From these relations it is clear that the granites are actually younger than the schists, and accordingly that the oldest of all accessible

rocks at the earth's surface are the metamorphosed equivalents of ordinary types of sedimentary rocks, of lava flows, and in some cases of intrusive rocks injected into these. What may have composed the surface on which the materials of the schists were laid down is unknown, but no rocks at the earth's surface can be identified definitely as part of an original crust. The observed conditions accord well with the inferred stages of earth development according to the planetesimal hypothesis, which holds that the geologic processes that caused erosion and sedimentation began long before the earth had reached its present size.

The most ancient rocks containing radioactive minerals so far known come from a locality in Russia. Reliable studies indicate that these rocks are about 1,852 million years old, but it is to be noted that still older nonradioactive rocks occur in this region.

DISTRIBUTION AND GENERAL CHARACTER OF PRE-CAMBRIAN AREAS IN NORTH AMERICA

Pre-Cambrian rocks occur at the surface, or immediately underlie unconsolidated surficial materials, in about 30 per cent of the area of North America. Much the greater part of this pre-Cambrian area lies in the northern part of the continent, comprising almost all of Canada north of the St. Lawrence River and the Great Lakes, and east of Lake Winnipeg and the Mackenzie River. This region is known as the Canadian Shield. Outlying portions of the shield include the Adirondack Mountains of northeastern New York and the highlands of northern Wisconsin, south of Lake Superior.

Pre-Cambrian rocks are prominent also in Newfoundland, Nova Scotia, New England, and in a broad belt comprising the easternmost part of the Appalachian Mountains and the adjacent Piedmont Plateau. The Interior Plains region of the continent contains a few small areas of pre-Cambrian exposures, as in the Black Hills of South Dakota, the Ozark region of Missouri, the Arbuckle and Wichita Mountains of southern Oklahoma, and the Llano region of central Texas. Several parts of the Cordilleran district in western North America show large outcrops of pre-Cambrian rocks, especially in the Rocky Mountains system.

It is desirable to note briefly the general character of these regions composed of very ancient rocks.

Canadian Shield.—The portion of North America included in the Canadian Shield is preeminently a land of lakes, of clear-water streams with rapids and falls, of ill-drained swampy and marshy areas, and of limitless conifer forests. In the far north there are grass lands and treeless tundras. Rock surfaces devoid of soil are common in many places. The geologic structure is very complex and there is much variation in the hardness of the rocks. As a result of these conditions, mainly, the topography is locally rugged. The amount of relief in any one area is not

great, however, and an outstanding feature of the country as a whole is the remarkably even skyline, which is clearly a mark of peneplanation. The Canadian Shield region has probably been a persistent lowland that mostly has stood very close to sea level. From time to time in the course

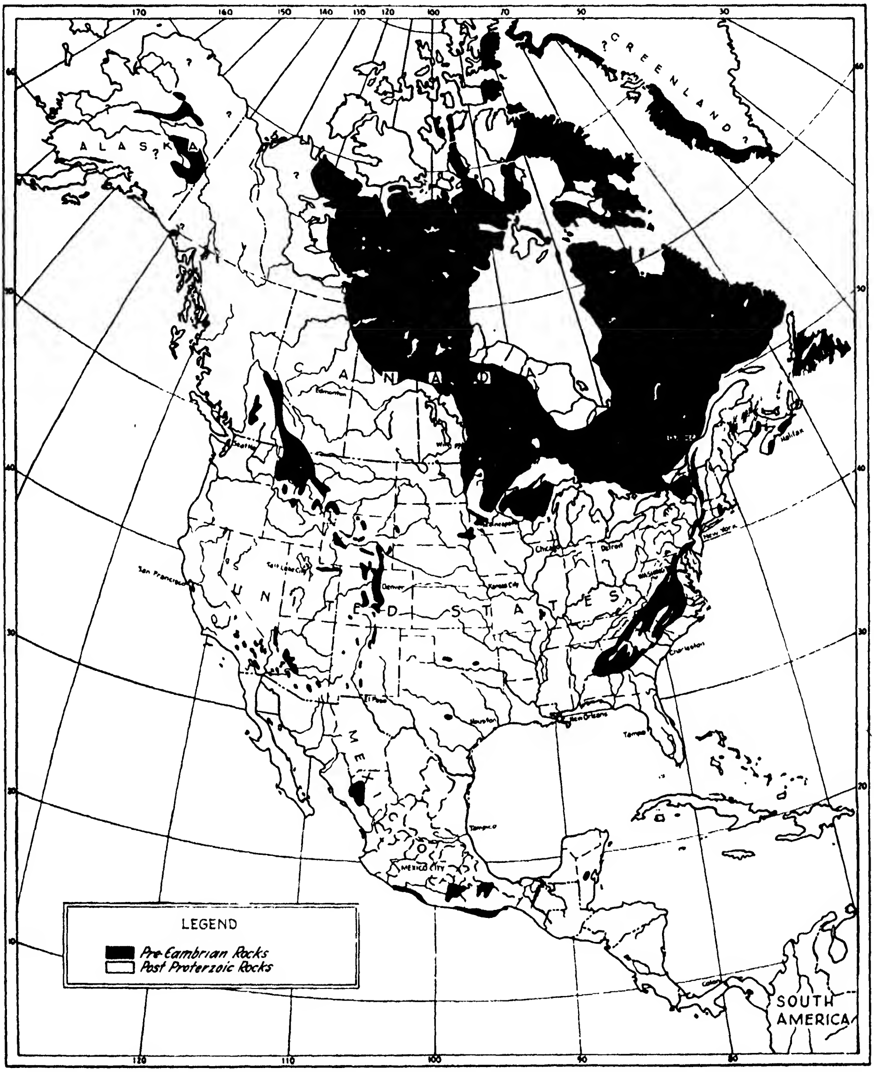


FIG. 30.—Map showing distribution of pre-Cambrian outcrop areas in North America.

of geologic history it appears to have been partially and temporarily submerged. The present irregularities of the land in this region are due chiefly to differences in hardness of the rocks and effects of very recent glaciation. The ice sheets carried away huge quantities of the former residual soils. The uneven erosion and deposition of the glaciers made

innumerable depressions that are now occupied by lakes and swamps and created conditions that profoundly affect drainage and the work of streams.

The Adirondacks are a group of mountains in northeastern New York. Topographically, the mountain area is very prominent, for some of the peaks rise nearly 5,000 feet above the adjacent lowland country. The mountains have rounded rather than angular outlines, and their slopes and summits are densely clothed with forests. There are deep valleys, some of which contain beautiful lakes.

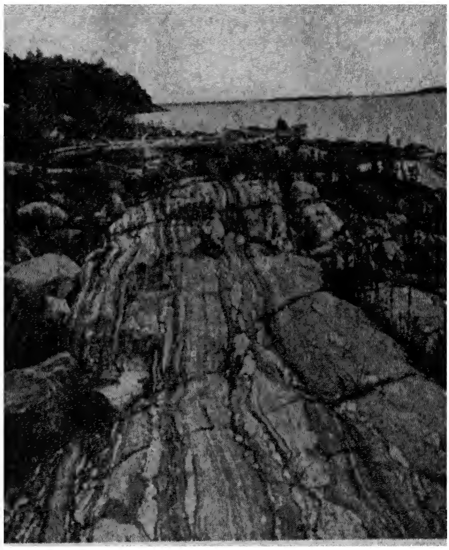


FIG. 31.—Crystalline rocks of complex structure, peneplaned by streams and eroded by ice, compose most of the Canadian Shield. Schist on the shore of Lac la Ronde, Manitoba. (*Geol. Survey Canada.*)

The northern Wisconsin Highlands and the northeastern portion of Minnesota are essentially similar to typical parts of the Canadian Shield lying north of the Great Lakes. As a matter of fact, these areas in the United States may be properly considered as a southern extension of the Canadian Shield. Like other parts of the shield, this region has been peneplaned and has been affected by glaciation.

Appalachian Region.—Pre-Cambrian granites, gneisses, and schists have extensive distribution and exert an important influence on the topography in parts of most of the Atlantic seaboard states. The Blue Ridge, which comprises the main eastern front of the mountains, is composed of pre-Cambrian and some Lower Cambrian rocks. The same may be said of the strongly elevated portion of the Appalachians in northwestern North Carolina and adjacent territory. The topography of this region is more truly mountainous than that of any other portion of the eastern

United States. Mount Mitchell in North Carolina (elevation, 6,711 feet) is the highest point in the United States east of the Rockies. The rugged mountains and hills are covered with dense forests, and certain sections contain only the merest sprinkling of population.

The Piedmont Plateau is a peneplaned east-sloping upland on the east side of the Appalachian Mountains district. Its altitude ranges from about 1,500 feet on the west to 400 feet or less on the east, where it is differentiated from the Coastal Plain in many places by low bluffs or strongly marked slopes. The border, which is commonly designated as the "fall line," is marked also by steepened descent of streams, with common occurrence of low falls or rapids. Because of water power that

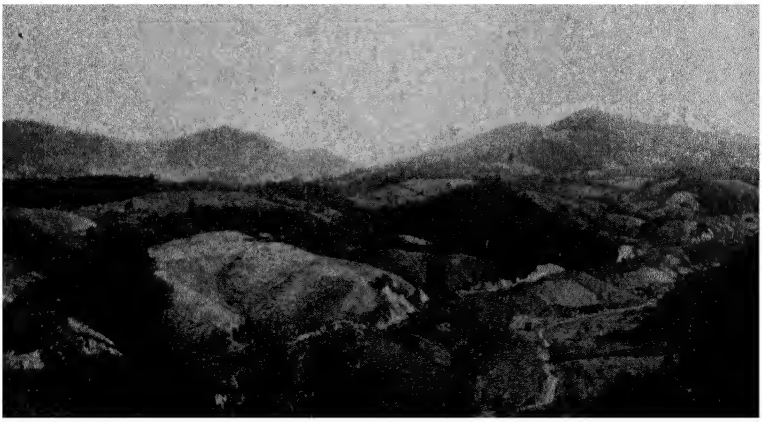


FIG. 32.—Mountains of Archean gneiss in western North Carolina. (*Arthur Keith, U. S. Geol. Survey.*)

is developed where swift-flowing streams of the Piedmont region pass from the resistant pre-Cambrian rocks to the gentle gradients developed on weak beds of the Coastal Plain, and because in many cases this boundary marks the head of tidewater, a number of settlements that have grown to be important cities are located along this line. Slight uplift in comparatively recent geologic time has led to partial dissection of the Piedmont Plateau surface by stream erosion. The topography in many places may be described as gently rolling, but locally there are fairly deep, narrow valleys. The structure of the rocks is very complex, and the comparative evenness of the upland surface (that is, the general accordance of hilltop levels) points to a former prolonged peneplanation. This is also borne out by the generally deep character of the residual soils and the extensive decomposition of the crystalline rocks, especially in areas along divides where work of recent erosion has not yet cut down to fresh rock. Locally, there are large tracts of forest, either never cleared or second growth.

Central Plains Region.—Rounded hills of pre-Cambrian igneous rocks, covered thickly with forest growth, rise several hundred feet above the general level of the Ozark Highlands, some 70 miles south of St. Louis, Mo. This small area is known as the St. Francis Mountains.

Rather similar features appear in the Wichita Mountains of southern Oklahoma and in the Black Hills of South Dakota, but in both of these places the forest cover is not dense, there are numerous exposures of bare rock, and effects of erosion are seen in sharply pointed peaks and spires. Pre-Cambrian exposures in the Arbuckle Mountains occur in prominent hills and also in broad, inconspicuous flattish areas, where the rocks have been peneplaned by erosion.

The granite, schist, and other crystalline rocks of pre-Cambrian age that are exposed in the Llano region, a few miles northwest of Austin, Texas, form low hills with fairly accordant summit levels.

Cordilleran Region.—Very ancient granites, gneisses, schists, and other crystalline rocks compose the core of the Rocky Mountains, as is very well shown in Colorado. Pikes Peak and other lofty mountains of this region are composed of pre-Cambrian rocks that, through agency of crustal deformations in more recent geologic time, have been pushed upward to elevations of more than 14,000 feet. Erosion, mainly by running water and ice, has carved innumerable deep canyons, cirques, U-shaped valleys, and imposing sheer cliffs. The lower slopes of not too great steepness are forest-clad, but above timber line there is bare rock. Some of the canyons, like that of the Big Thompson Valley which is followed by a highway leading to Rocky Mountain National Park, give excellent exposures of steeply dipping quartzites and other pre-Cambrian rocks. Evidence that the enormous granitic mass of the Rockies is pre-Cambrian in age, rather than the results of much later magmatic intrusion, is shown by the contact between the Cambrian and the granitic mass. The unconformable relationship between these rocks is clearly indicated by the smoothly beveled surface of the granite at the base of the Cambrian strata, as readily seen on some of the roads west of Colorado Springs and elsewhere.

Parts of the northern Rockies, as in Montana and British Columbia, contain a very great thickness of pre-Cambrian stratified rocks, mainly quartzite, slate, and limestone, which in general are surprisingly little disturbed by folding. They have been profoundly dislocated in some places by faulting, however, and they have been elevated many thousands of feet. Erosion agencies have carved in them some of the most imposing mountain scenery of the continent. The great mountains and lakes of Glacier National Park are a typical and most accessible portion of this mountain area.

Granite, schist, and more or less metamorphosed sedimentary rocks are exposed for scores of miles in the bottom of the Grand Canyon of the

Colorado in Arizona. There are smaller exposures also in other canyon valleys. Southwestern Arizona and parts of the Great Basin contain many hills and mountains composed of pre-Cambrian crystalline rocks.

Pre-Cambrian rocks are known in the Klamath Mountains of northern California and it is possible that some of the granitic and other crystalline rocks of the Sierra Nevada and Coast Ranges are pre-Cambrian in age. The topography of the crystalline rock areas of these mountains is very similar to that of the Rockies.

PRE-CAMBRIAN AREAS OF OTHER CONTINENTS

Areas of pre-Cambrian rocks are known on all of the continents. As in North America, the larger outcrop areas are mostly lowlands that have been occasionally and partially submerged by shallow seas of Cambrian or later time but that have tended to remain as persistent land masses. They are the nuclear portions of the continents. The cores of mountain uplifts are commonly found to consist of pre-Cambrian crystalline rocks.

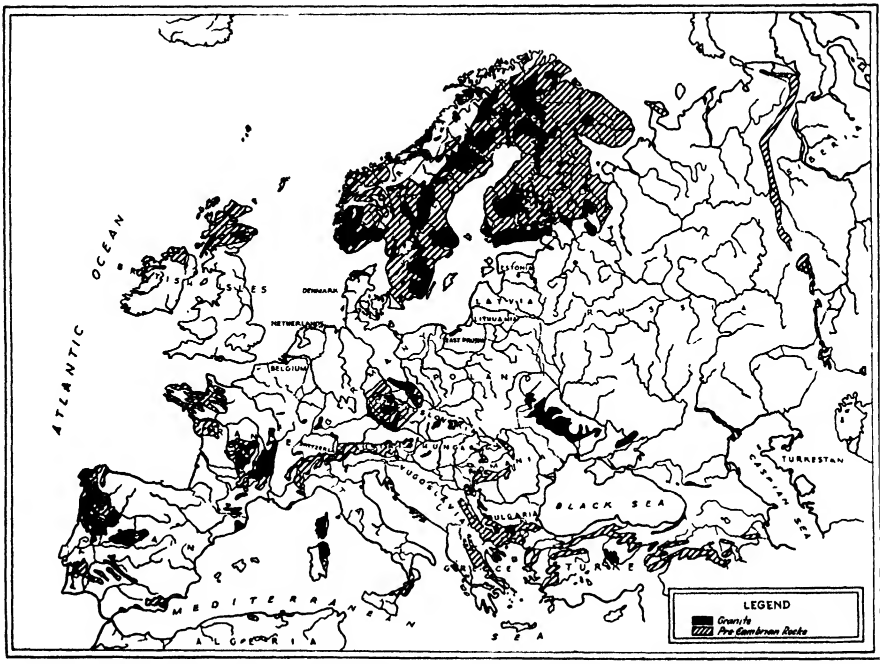


FIG. 33.—Map showing distribution of pre-Cambrian outcrop areas in Europe.

Europe.—The largest continuous tract of pre-Cambrian rocks in Europe occupies the northwestern part of the continent, in Scandinavia and Finland. Topographically and geologically there are many points of resemblance between this ancient-rock area of the Old World and the Canadian Shield. Granitic and highly complex metamorphic rocks of Archeozoic age are recognized, and there are thick series of more or less metamorphosed sedimentary rocks of Proterozoic age that are separated by unconformities and some of them intruded by batholiths of granite. The rocks of western

Scandinavia have been subjected to greater metamorphism than those of the eastern part of the peninsula.

The Northwest Highlands of Scotland afford excellent exposures of pre-Cambrian rocks and this has been a region of much careful study. A "fundamental complex" composed dominantly of igneous rocks and subordinately of highly metamorphosed rocks is termed the Lewisian system. It is Archeozoic in age. Resting unconformably on these mainly granitic rocks is the Torridonian system of Proterozoic age. It consists mainly of sandstone beds in which the order of succession is clearly observable. The pre-Cambrian rocks of this region have been disturbed by a remarkable series of great thrust faults that have pushed the rocks from east to west in successive slices.

Pre-Cambrian rocks occur in Russia and in several parts of central Europe, the latter comprising mountain uplifts of both ancient and geologically recent date. One of the latter is the Alps, where pre-Cambrian crystalline rocks have been overthrust on Mesozoic and Cenozoic strata. From a Russian locality (Sinyaya Pala, Carelia) comes a pre-Cambrian rock sample, uraninite, that according to reliable measurement of radioactive disintegration products proves to be the oldest rock thus studied. Its age is computed to be 1,852 million years.

Asia contains extensive outcrops of pre-Cambrian rocks, especially in east central Siberia, China, Mongolia, and India. The succession of rocks is more completely determined in northern China than in most other places. Archeozoic and Proterozoic formations are clearly differentiated. Much of western *Australia* shows pre-Cambrian rocks at the surface. A variety of rocks of pre-Cambrian age occur in southern *Africa*, and Archean granite and other rocks are known in the northern part of the continent. A large territory in the northeastern part of *South America* is composed of Archeozoic and Proterozoic formations. Extensive exposures of pre-Cambrian rocks appear also in the Andes Mountains.

SUMMARY

The great unconformity that occurs everywhere at the base of the oldest fairly abundantly fossiliferous rocks (Cambrian) is an important geologic datum that separates the very ancient from the comparatively young formations.

The pre-Cambrian rocks are almost entirely unfossiliferous and therefore the problem of determining the relative age and order of succession of different formations must be attacked by study of physical characters. Of these the most significant are (1) lithologic characters, (2) order of superposition, (3) general structure, (4) occurrence of unconformities, and (5) determination of age by measurement of radioactive disintegration products.

Two main divisions of the pre-Cambrian rocks are recognizable: (1) a younger part composed dominantly of sedimentary rocks in which the order of succession is definitely determinable, and (2) an older part distinguished by dominance of highly metamorphosed and deep-seated igneous rocks. These represent the Proterozoic and Archeozoic sequences, respectively. Since the intrusive igneous rocks of the Archeozoic extend into and cut across schists, the latter are the older. These schists are metamorphosed sedimentary and volcanic rocks and are the oldest known rocks.

The chief area of exposure of pre-Cambrian rocks in North America is the Canadian Shield, which comprises most of the northeastern part of the continent. This is a peneplaned region that has been much affected by recent glaciation. The Adirondack Mountains of northeastern New York and the northern Wisconsin Highlands are southerly extensions of the Canadian Shield. Pre-Cambrian rocks are extensively distributed in the eastern Appalachian Mountains and Piedmont Plateau region, and parts of the western Cordillera. Small outcrops of pre-Cambrian rocks occur in local uplifts of the Interior Plains region.

Pre-Cambrian rocks that are similar in general character to those of North America occur on each of the other continents.

CHAPTER VII

THE FORMATIONS AND HISTORY OF THE ARCHEOZOIC ERA

The Archeozoic era is the oldest part of geologic time represented by rocks at the earth's surface. Possibly a better designation would be Archeozoic eon, for it is likely that there are several great eras in the ordinary geologic sense in this enormously long initial unit of the time scale. But the threads are so inextricably tangled that the detailed record of this part of earth history may never be determined. The rocks of this age are commonly designated as *Archean,* and they are also appropriately termed "basement complex." The lower limit of the Archean rocks and the beginning of Archeozoic time are entirely unknown.

The name Archeozoic, signifying "initial life," implies that the era should be defined to begin with the beginning of life on the earth. According to the planetesimal hypothesis, this was probably some time before the earth had reached its full size. The close of the era is marked by widespread erosion which produced an important unconformity. Thus delimited, the Archeozoic comprises the first portion of earth history which, at least in part, is recorded by rocks accessible at the earth's surface. The Archean rocks are exclusively of igneous and metamorphic types and are distinguished by remarkable complexity of structure.

ARCHEAN ROCKS OF THE CANADIAN SHIELD AND THEIR HISTORY

The northeastern part of the North American continent, comprising central and eastern Canada (the Canadian Shield), is the classic region of the world for study of the Archean rocks. Most of the observations which bear on their classification and geologic history have been made along the St. Lawrence and near the shores of Lake Huron and Lake Superior.

Keewatin and Related Rocks.—In the country north of Lake Superior, stretching from Winnipeg a thousand miles or more eastward, are exposures of schists and greenstones that have been named Keewatin. They consist in part of water-laid sedimentary rocks, limestone, shale, sandstone, and conglomerate that have been much altered by metamorphism, and in part of lava flows and tuffs that have been altered to form greenstone. A pillowy structure frequently observed in the latter indicates that the lava flows took place under water. The amount of volcanic material is greater in the higher, younger part of the series.

Locally, as in the Vermilion district of northeastern Minnesota, iron ore occurs.

According to some geologists, a series of metamorphosed sediments (Coutchiching) underlies the Keewatin in the region northwest of Lake Superior. Probably most of these schists should be included with the Keewatin, but some have been found to be younger than Keewatin.

East of Lake Huron there is a tremendous thickness of altered limestone with subordinate shaly, sandy, and conglomeratic sediments, known as the *Grenville* series. These rocks, which are very unlike the Keewatin, form much of the surface in eastern Ontario, Quebec, Labrador, and the Adirondack Mountains of northeastern New York. It is

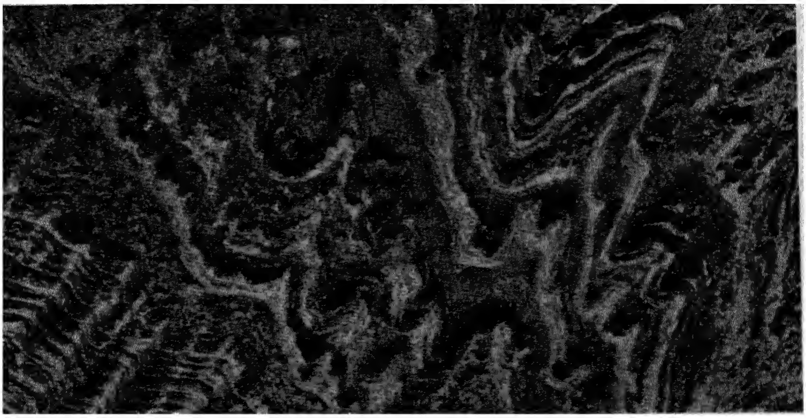


Fig. 34.—Crystalline limestone and amphibolite (Grenville) in the Laurentian region (Haliburton area) north of Lake Ontario, Canada. (*Geol. Survey Canada.*)

possible that this great calcareous deposit, notwithstanding difference in lithologic character, corresponds in age to some of the sedimentary series within the Keewatin, but some recent work (Collins and Quirke) suggests that it may actually be of Proterozoic age.

The metamorphism of the Keewatin and related rocks was accomplished largely during Archeozoic time, as may be seen from the lesser alteration of superposed younger rocks, but it is obvious that all post-Archeozoic diastrophism must contribute to complication of structures in the Archean. In some regions where Paleozoic and Mesozoic rocks have been contorted and metamorphosed by crustal movements, the underlying Archean rocks cannot fail to have suffered changes that have imposed complexity on complexity.

Laurentian Rocks.—Granites and gneisses named Laurentian cover thousands of square miles in the Canadian Shield region. As has been indicated, the nature of the contact between these granites and the schists shows clearly that the granites are the younger. Granite batholiths are deep-seated intrusions in which the characteristic coarse texture

is developed by reason of slow cooling and possibly other physicochemical conditions. Much of the Laurentian magmas must have congealed at a depth below the surface that is measured in thousands of feet. The foundering of portions of the batholith roofs, however, and the assimilation of magmatic matter by the rocks above the batholiths may have produced granitic textures at moderately shallow depths. In any case, the present very extensive exposure of these rocks means that the original cover of the batholiths—the material into which the magma was intruded—has been removed by erosion, and in addition an unknown thickness of the granite itself has been worn away. There is evidence, to be noted later, that a large part of this tremendous erosion was accomplished before the beginning of Proterozoic sedimentation.

The gneisses are banded granitic rocks in which parallel arrangement of minerals was produced by movement in the magma as it solidified, or by regional metamorphism of granites subsequent to solidification, or by the more or less complete fusion (or metamorphic reconstruction) of sedimentary rocks at great depth.

The Laurentian Revolution.—Shortening of the earth's crust due to mountain-building compression causes folding of strata, thrust faulting, and if the pressures are sufficient may produce foliation and schistosity. The trend of the axes of folding and faulting is approximately at right angles to the pressures. Erosion of the deformed rocks results in strongly defined bands of outcrops, which run subparallel to the axes of the folds and faults and likewise to the strike of lamination in the schists. All of this is roughly comparable to the grain in wood, and accordingly the term *grain* is useful as applied to country which shows a marked orientation of structures.

In the Laurentian region the granitic masses and gneissoid banding as well as the structure of metamorphosed sedimentary rocks show such a grain, trending about N. 70 E. The very strong deformation of the rocks which is thus indicated implies a mountain-making crustal movement which occurred in the latter part of Archeozoic time. The intrusion of granitic rocks was evidently approximately contemporaneous with this disturbance and illustrates the general association of igneous intrusion on a large scale with mountain-building forces. The compression of the southeastern part of the Canadian Shield which developed these structures must have produced an important range of mountains, which are named the Laurentian Mountains. Erosion, which became active as soon as the rocks were elevated, would carve canyon valleys and in time would obliterate even the greatest mountain chain, leaving only the geologic evidence which is seen in the complex structure and banded outcrops of the former mountain roots. The time required for such profound erosion is necessarily great. We may call it the post-Archeozoic erosion interval.

The unconformity above the Keewatin and Laurentian rocks and beneath beds classed as Huronian in the Lake Superior district is generally regarded by geologists of the United States as the principal break in the pre-Cambrian, separating a "basement complex" classed as Archean from prevailingly sedimentary rocks classed as Proterozoic (Algonkian). This unconformity is very conspicuous in Michigan and Wisconsin. In Minnesota and Ontario, however, the unconformity, while definitely proved, is overshadowed by the structural discordance at the top of slaty deposits (Knife Lake series of Minnesota, Doré series of Michipicoten district north of Lake Superior) that are younger than Keewatin. The post-Keewatin slates, accordingly, are included by some geologists in the Archean and the unconformity above the slates is said to represent the "ep-Archean" (that is, post-Archeozoic) erosion interval. Thus, there is divergence of opinion as to which of two important unconformities should be employed in dividing the Archeozoic and Proterozoic.

The very great area of Laurentian granites, as formerly supposed, has been cut down enormously in late years by discovery of the importance of younger pre-Cambrian granites. Most of the "Laurentian" thus proves to be Proterozoic and there are relatively few areas of undoubted pre-Proterozoic granites. This may even apply to the type Laurentian, for if the Grenville sediments that are invaded by this granite are partly or wholly of Proterozoic age, the igneous intrusions cannot be Archeozoic. Yet there are places where metamorphosed Archean rocks are intruded by granite of pre-Proterozoic age, and there is evidence of mountain-making disturbances and great erosion that closed the Archeozoic era. These considerations, then, apply mainly to use of the word "Laurentian."

ARCHEAN ROCKS IN OTHER REGIONS

Surface Distribution.—Rocks having the complex structure and character of the Archean formations as seen in the Canadian Shield make up the central part of the Adirondacks in northeastern New York, which is really an extension of the Canadian Shield. They occur throughout much of New England and are exposed at intervals southward along the east side of the Appalachian Mountains as far as north central Alabama. Most of the outcrops occur in the Piedmont province which borders the Atlantic Coastal Plain, rather than in the mountains proper. The rocks consist of various types of gneisses and schists, some of the latter being identifiable as metamorphosed sedimentary rocks.

Farther west, rocks which are probably Archean are exposed in the core of the Ozark Uplift south of St. Louis, the mountains of southern Oklahoma, the Llano region of Texas, the Black Hills and Rocky Mountains, and in a large part of the Great Basin country southward into Mexico. In some of these areas the granitic rocks are little metamorphosed and may be as young as Proterozoic. There are minor variations in the kind of rocks in these different regions, but all are dominantly composed of schist, granite, or both, and the structure is very complex. Correlations of these rocks in different regions are undependable.

Archean rocks are very widely distributed in other parts of the world, occurring on every continent.

Continuity of the Archean beneath Younger Rocks.—Many deep wells located in areas outside the exposures of pre-Cambrian rocks have penetrated all of the overlying younger strata and passed into Archean or Proterozoic rocks. Since the Archean is known to be present wherever erosion has sufficiently removed the younger rocks and exploration in drilling has gone sufficiently deep, and since the Archean probably includes a considerable but unknown thickness of the outer earth shell, the conclusion is advanced that these ancient rocks are continuous laterally

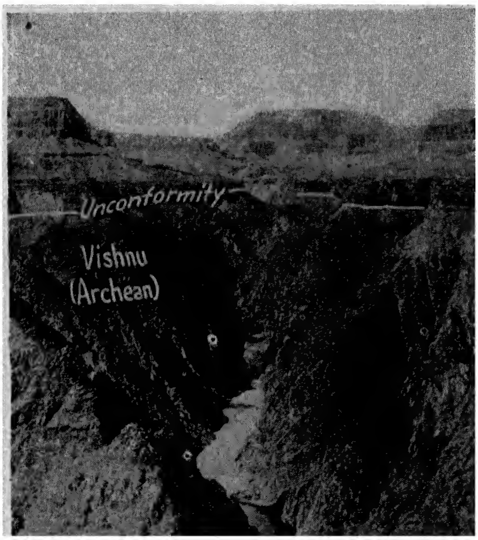


Fig. 35.—Archean rocks consisting of schist, granite and pegmatite in the Granite Gorge, Grand Canyon of Colorado River, Arizona. (*N. W. Carkhuff, U. S. Geol. Survey.*)

all over the world. The Archean is universal beneath continents and oceans, and it is the only division of rocks of which this can be said.

Theoretically, the Archean may be interrupted locally by masses of intrusive rock of younger age, for, of course, all igneous invasions from the earth's depths must penetrate a part of the Archean, except those that may originate in exceptionally thick and greatly depressed post-Archean rocks. In some cases, as along the east side of the Appalachians where granitic batholiths of Late Paleozoic age intrude Archean and younger rocks, it has been possible to distinguish the post-Archean age of such intrusions, but this is not generally possible. It should be recognized, therefore, that much of the igneous materials of certain Archean areas is younger than Archean.

PHYSICAL CONDITIONS AND DURATION OF ARCHEOZOIC TIME

The fact that muds, sands, and calcareous sediments, totaling in various places many thousands of feet, were deposited during Archeozoic time indicates that the geologic agencies of erosion, transportation, and sedimentation were operative at that time in about the same manner as in later eras of earth history. Although metamorphism has largely masked the original character of these sediments, there is no indication of exceptional physical environment unless it be a lack of vegetal covering of the lands. Locally we find indication of very active vulcanism. Nothing is known of climate except that almost certainly it was suited to the existence of life. Discussion of the beginning and early development of life is reserved to a later chapter.

The Archean is characterized by an unusual proportion of deep-seated igneous rocks now appearing at the surface, but this does not by any means indicate a generally molten condition of the surface part of the globe. However, crustal disturbances, accompanied by metamorphism and by intrusion of igneous rocks, took place on a very large scale. The intense heat from igneous magmas and from the depths of the earth, and the action of mineralizing solutions and vapors derived from the great magmatic invasions, caused profound changes in existing rocks by recrystallization and the formation of new minerals.

Except to say that Archeozoic time was very long, perhaps exceeding in length all of subsequent geologic history, no definite statement concerning duration is possible. Time represented by the Archean rocks that can be seen at the earth's surface probably represents many scores of millions of years and to this may be added the long time representing the Laurentian mountain-building and the post-Archeozoic erosion interval. According to the planetesimal hypothesis, the vastly greater part of the Archean rocks and of Archeozoic time are not represented by any rocks now exposed. According to studies of radioactive minerals, parts of the Archean are determined to be at least 1,850 million years old.

SUMMARY

The Archean rocks, from which earth history in the Archeozoic era is inferred, are very widely exposed throughout the world wherever younger rocks have not been deposited or where they have been eroded away. The Archean is thought to be continuous beneath all younger deposits. The Archean formations consist of schist and allied highly metamorphosed rocks, on the one hand, and of granitic or gneissoid rocks intrusive into the schists, on the other. The schists represent an unknown number of periods of sedimentation, in part accompanied by much vulcanism; these periods were doubtless separated by times of crustal disturbance and igneous intrusions that built mountains, and by prolonged erosion

intervals. Occurrence of great quantities of sedimentary materials implies normal conditions of erosion and sedimentation, comparable with later times, and the existence of life is indicated on indirect evidence. The structure of Archean rocks is characteristically so complex that most of the historical record is indecipherable. Mountain-building that occurred near the close of the era is called the Laurentian revolution, but much of the deformation of Archean rocks may be due to earlier mountain-making disturbances. There was a long period of erosion at the close of Archeozoic time.

CHAPTER VIII

THE FORMATIONS AND HISTORY OF THE PROTEROZOIC ERA

The second major division of earth history that is decipherable by study of rocks exposed at the earth's surface is the Proterozoic era. The name, which signifies "very early life," is appropriate because the plants and animals of this time were assuredly primitive as compared with later organisms. Some European geologists, mainly British, have employed Proterozoic in a different sense and some Americans use the name Algonkian as applied to the rocks that are intermediate in age between Archean and Cambrian. There is a growing tendency, however, to define Proterozoic as we shall treat it here.

Definition and General Character of the Proterozoic Rocks.—The Proterozoic rocks include all of the stratified rocks, sedimentary or extrusive volcanic in origin, that occur unconformably above the complexly folded and metamorphosed Archean rocks and unconformably beneath the Cambrian; and in addition they include intrusive igneous rocks that penetrate these post-Archean rocks but do not intersect Cambrian or younger strata. The Proterozoic age of the intrusive rocks is clearly shown where they invade Proterozoic sediments and show effects of erosion preceding Cambrian sedimentation; but in certain cases, as where post-Proterozoic strata are absent in a region, it may not be possible to differentiate Proterozoic from younger intrusive igneous rocks.

In general, the Proterozoic rocks offer strong contrast to the Archean rocks, for the former are dominantly sedimentary in origin, comparatively simple in structure except locally, and as a whole little altered by metamorphism, while the latter are mainly igneous, highly metamorphosed, and very complex. It is true that sandstones have commonly been changed to quartzites, shales to slaty rocks, and limestones to marble, but only in part has folding been extreme and the effects of heat and pressure such as to produce well-defined schistosity. In some regions, as east of Lake Huron, metamorphism of the Proterozoic rocks is so extreme that it is all but impossible to distinguish them from the Archean rocks.

The Proterozoic formations are distinguished from Paleozoic and younger rocks mainly by the nearly complete absence of fossils. There are very thick deposits of conglomerate, quartzite, slaty shale, limestone, and red beds; and in places there are sheets of glacial debris, hardened and cemented into stone (tillite). Another important type of sedimentary deposit is one consisting largely of iron compounds from which

great quantities of iron ore have been derived. Among igneous rocks there are granites, dark-colored intrusives (diabase, gabbro), porphyries, and lavas. The dark-colored basic rocks are associated in many places with occurrence of valuable mineral deposits, including especially silver, copper, and nickel.

Stratigraphic Relations.—The Proterozoic rocks rest on granite or schist of Archeozoic age, from which they are separated by a profound erosional unconformity. The magnitude of the unconformity is indicated by the fact that both granite and schist are deep-seated rock types which

FIG. 36.—Ripple-marked Proterozoic quartzite in the Medicine Bow Mountains, Wyoming. (*W. C. Alden, U. S. Geol. Survey.*)

can normally be exposed at the earth's surface only by erosion of the great thickness of rock that formerly covered them. The erosion that preceded Proterozoic sedimentation produced in most places an even, nearly plane surface intersecting rocks of different hardness, and the originally horizontal or nearly horizontal attitude of this erosion surface is proved by the fact that bedding planes in the immediately overlying Proterozoic strata are essentially parallel to it.

The unconformity at the top of the Proterozoic formations cuts across layers of different age, from youngest to oldest. In places, as in parts of the Lake Superior region and in western Montana and Alberta, there is only slight difference in the attitude of the Proterozoic and overlying Paleozoic sediments. Elsewhere, the older rocks are steeply inclined, while the Cambrian and younger strata may be nearly horizontal. Where Proterozoic rocks have been entirely removed by erosion or where they were never deposited, Paleozoic or younger beds may rest directly on Archean rocks. The general smoothness of the post-Proterozoic erosion surface indicates prolonged exposure to atmospheric agencies and thorough peneplanation, but locally there are hills of hard Proterozoic rocks that were not obliterated before burial by younger sediments.

Distribution of Proterozoic Rocks.—Rocks of Proterozoic age are widely exposed in parts of the Canadian Shield. They have been most

studied in the neighborhood of Lake Superior and Lake Huron, while very little indeed is known of exposures in northern parts of the continent. The Adirondack Mountains in northeastern New York consist of Grenville sediments and intrusive igneous rocks of post-Grenville age that may be Proterozoic. The easternmost part of the Appalachian Mountains and the Piedmont province contain extensive outcrops of Proterozoic rocks.

Small areas of pre-Cambrian rocks consisting of intrusive igneous rocks or highly metamorphosed schist occur in local uplifts of the continental interior, as in the Ozarks, Black Hills, southern Oklahoma, and central Texas. They may be of Proterozoic age, but it is possible that they are partly or wholly Archean. The same is true of a considerable part of the crystalline core of the Rocky Mountains, although in parts of Wyoming, Colorado, and various other places there are extensive exposures of very thick Proterozoic quartzites, slates, and limestones.

The Grand Canyon region affords excellent sections of a thick series of Proterozoic sediments which rest unconformably on Archean crystalline rocks. The greatest thickness of Proterozoic rocks in western North America is found in the Belt series, consisting of thousands of feet of quartzite, slaty shale, and limestone, which occurs in western Montana, northern Idaho, Alberta, and British Columbia. These rocks are especially well exposed in Glacier National Park.

The original distribution of Proterozoic rocks in North America and the places where Proterozoic sediments are present beneath concealing Paleozoic or younger rocks can only be guessed. The original extent of these rocks was certainly vastly greater than their present area of outcrop.

Factors Controlling the Nature of Proterozoic Outcrops.—The areas at the earth's surface where Proterozoic rocks now appear are controlled or modified by many factors. First, of course, possible outcrop areas are limited to places where Proterozoic rocks were once present and from which they have not been removed subsequently by erosion. The geographic extent and shape of the outcrop area and the nature of contacts with other formations depend in varying degree on (1) geologic structure, including attitude of the rock strata, interruption by faulting or igneous intrusion, and unconformities, (2) thickness of Proterozoic rocks, and (3) topography. The governing conditions are essentially geometrical and therefore apply to any group of rocks. As commonly understood, "outcrop" includes the area in which the rock formation is actually exposed or is concealed only by soil cover. The soil-mantled areas commonly exceed greatly the rock exposures, as in much of the Canadian Shield where forests, swamps, and lakes add difficulty to geological field work.

In the case of the Proterozoic rocks, outcrops are commonly bordered on one side by exposures of Archean rocks and on the other by post-

Proterozoic strata (Fig. 37*A*, *B*); this is in accordance with the age succession of the rocks. In many places, however, owing to folding, faulting,

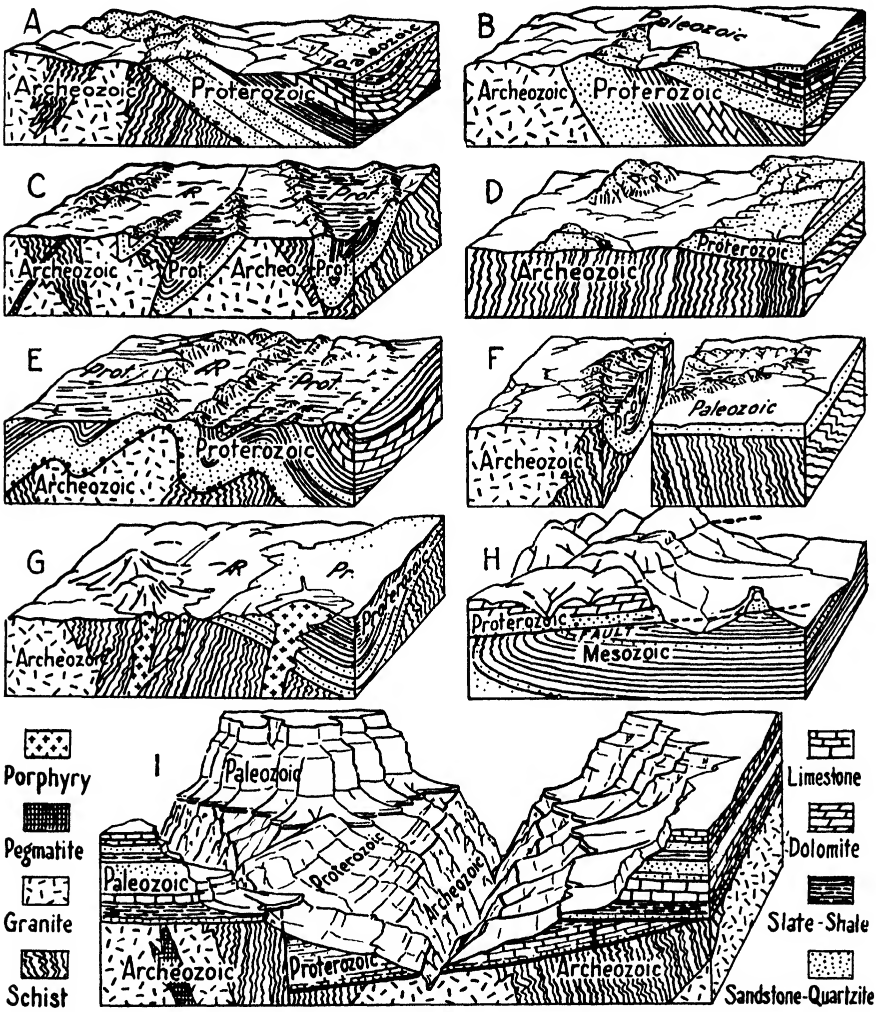


FIG. 37.—Diagrams showing the stratigraphic relations of Proterozoic formations to older and younger rocks, and consequent effects on outcrops.

(*A*) Proterozoic beds between Archeozoic and Paleozoic rocks. Note differences in structure. (*B*) Similar to (*A*), but the Paleozoic rocks overlap the Proterozoic formations. (*C*) Proterozoic outcrops surrounded by Archeozoic rocks, the location of the Proterozoic areas being due mainly to structure. (*D*) The same, but location of Proterozoic areas being due mainly to topography. (*E*) Archeozoic outcrop surrounded by Proterozoic outcrops. (*F*) Proterozoic outcrop surrounded by Paleozoic outcrops. (*G*) This diagram shows possible relations of Archeozoic and Proterozoic rocks to post-Proterozoic igneous intrusions. (*H*) Proterozoic rocks overlying Mesozoic strata, due to thrust-faulting. This relationship is observed along the Lewis overthrust near Glacier National Park. (*I*) Proterozoic rocks in a part of the Grand Canyon.

and erosion, exposures of Proterozoic rocks may be entirely surrounded by Archean (Fig. 37*C*, *D*). Proterozoic outcrops may enclose Archean (Fig. 37*E*) or may be surrounded by Paleozoic or younger rocks (Fig.

37*F*). It is well to review these different relationships, readily understood though they are, for all are significant from the viewpoint of geologic history.

Subdivisions.—The Proterozoic rocks are divisible into major and minor parts that are established on the basis of lithologic character, on the occurrence of unconformities, and to some extent on regional geologic structure. Igneous rocks are differentiated from those of sedimentary origin, and their relative age is ascertained by observation of contacts with the associated strata. Divisions based on kind of rocks constitute formations. The unconformities are of special importance because they interrupt the rock-forming processes and afford basis for separation of the strata into large natural units. In some cases the erosion which made an unconformity was preceded by folding of the rock strata, and possibly by intrusion of igneous rocks, and by metamorphism. In these cases the unconformity is striking, for when sedimentation was resumed after the time of erosion, the younger strata were deposited across the eroded edges of the older rocks. If there was igneous activity, the younger rocks may rest in places on the eroded surface of intrusive igneous rocks.

The lithologic character of the formations, their sequence, structure, and the interruptions marked by unconformities are all significant in interpreting physical history. The nature of the formations is likely to vary from place to place, however, and the unconformities that define major groups in one Proterozoic area may not be recognizable in another, especially if there is great distance between the areas. Consequently, it is necessary to study each of the main Proterozoic areas independently and then to compare the records as closely as possible. The most complete record of conditions and events in Proterozoic time is afforded by the largest areas of exposed Proterozoic rocks, which in North America occur in the southern part of the Canadian Shield. This region, which has been studied in more detail than any other, is considered to offer the type Proterozoic section. In this section five main units or systems of rocks may be distinguished; in order from oldest to youngest, these are the Timiskaming, Lower Huronian, Middle Huronian, Upper Huronian (Animikian), and Keweenawan.

PROTEROZOIC ROCKS OF THE CANADIAN SHIELD

Consideration of the Proterozoic rocks of the Canadian Shield is naturally divided into two or perhaps three parts, because the areas in which fairly accurate knowledge is available are geographically separated by large areas of granite, by unexplored territory, or by a covering of Paleozoic rocks and water of the Great Lakes. The nature of the rocks that are found in these areas differs to some extent, and the problem of

determining the age and correlation of equivalent rocks in the different districts remains in part to be solved.

The first of the Proterozoic areas that we may differentiate is the Timiskaming region which lies in western Ontario due north of Lake Huron. It includes the original Huronian area where stratified rocks younger than Archean and older then the Cambrian were first recognized by Logan. Partly because of important deposits of gold, silver, nickel, and other metals in this district, Canadian geologists have given much study to this territory, but it is by no means completely surveyed.

A second important region lies southwest and in part northwest of Lake Superior. It is termed the Lake Superior region, and because of great deposits of iron and copper it has been specially studied by many geologists of the United States.

A possible third region is the St. Lawrence country, including both a part of eastern Ontario and the Adirondack region in northeastern New York. The rocks of this district have been generally thought to belong mostly to the Archean, but it is possible that they are actually Proterozoic.

The Timiskaming Region

The Timiskaming region comprises a part of western Ontario, extending some 300 miles eastward from the southeast shores of Lake Superior and about 100 miles northward from Georgian Bay which adjoins Lake Huron on the north and east. As indicated by the nature and thickness of the rock formations and by their structure and relations to one another, the Proterozoic history of this part of the Canadian Shield is very long and complex.

Timiskaming System.—Resting unconformably on crystalline and highly metamorphosed rocks of Archean age is a thick system of sedimentary rocks that has been called Timiskaming (or "pre-Huronian series," by some Canadian geologists). The sediments consist of conglomerate, quartzite, graywacke,[1] and slate, and their total thickness is at least several thousand feet. These strata have been extensively folded and considerably metamorphosed, and accordingly the rocks now appear in steeply dipping layers. Various locally named rocks (Sudbury, Steeprock, and Seine series, etc.) have been correlated with the Timiskaming rocks (E. S. Moore, 1929).

Folding of Timiskaming Rocks and Intrusion of Algoman Granite.—The fact that folding and metamorphism of the Timiskaming rocks occurred before the deposition of the next younger system of sediments found in this region is shown by the observations that (1) the folded and

[1] Graywacke is a somewhat metamorphosed shaly sandstone, generally gray in color, containing, besides quartz grains, abundant feldspar and other minerals and small rock fragments.

metamorphosed pre-Huronian or Timiskaming rocks are unconformably overlain by the Huronian, and (2) the Timiskaming rocks are observed in places to be penetrated by intrusions of granite which are older than the Huronian. The granite not only fails to penetrate the Huronian rocks but forms part of the surface on which these younger strata were deposited. The intrusions are obviously much younger than those called Laurentian, of Archean age, because they invade parts of this post-Archean sedimentary system. The post-Timiskaming granite has been named the *Algoman granite.*

History of Timiskaming Time.—The history indicated by the rocks described includes deposition of a huge thickness of sediments derived by erosion of Archean rocks in portions of the continent that stood relatively higher. Parts of the deposits may have been stream-laid, but probably most of them were formed at the bottom of a shallow sea that flooded the borders of the Canadian Shield. Some beds may be of glacial origin (Coleman). The sediments accumulated on an extensive erosion surface that had been formed at the close of Archean time. After Timiskaming deposition there was considerable crustal disturbance which folded and faulted the rocks profoundly and there were large intrusions of granitic magma. These igneous intrusions contributed to the metamorphism of the pre-Huronian rocks. Then there was general and very prolonged erosion which largely obliterated hills and mountains that had been formed. The land surface on which the Huronian deposits were laid down was essentially horizontal, as shown by the fact that stratification planes in the lower part of the Huronian system are approximately parallel to the underlying old-rock surface. According to Canadian geologists, the pre-Huronian erosion interval was one of the most important in the pre-Cambrian history of this region.

Huronian System.—The succession of rocks called Huronian rests unconformably on the plane of erosion which was developed after Timiskaming sedimentation and the subsequent folding and granitic intrusion. The deposits consist of conglomerate, quartzite, marble, and graywacke, their total thickness in this region being approximately 12,000 feet. In different places the Huronian rests on different kinds of older rocks, and, accordingly, the conglomerates at the base of the Huronian contain pebbles and cobbles of many kinds derived from these pre-Huronian rocks.

Many of the sedimentary rocks have a decidedly modern appearance, which indicates that essentially the same conditions and processes were operative in Huronian time as have characterized much later parts of geologic time.

Bruce and Cobalt Series.—The presence of an important disconformity within the Huronian rocks of the Timiskaming region shows that sedimentation was interrupted for a time and that in places a considerable

part of the Lower Huronian (Bruce series) sediments was removed by erosion before sedimentation was resumed (Cobalt series). The fact that the rocks above and below the disconformity are essentially parallel indicates absence of folding of the older series.

Glacial Deposits of the Cobalt Series.—The first deposit above the disconformity consists of a boulder conglomerate which is really a solidified deposit of glacial till (*tillite*) and associated water-laid sediments. This tillite contains striated stones, which with the presence of large boulders of different kinds of rock and other physical characters of the deposit clearly indicate action of continental glaciers. The deposit is

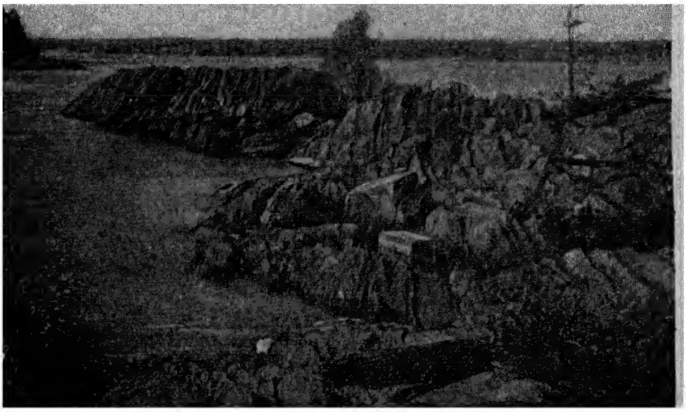


FIG. 38.—Steeply folded and metamorphosed Huronian limestone on the northeast shore of Lake Huron. The even skyline shows part of the Laurentian peneplain. (*T. T. Quirke, Geol. Survey Canada.*)

traceable for some hundreds of miles in the country north of Lake Huron, and it is doubtfully recognized also far to the northeast of this area.

Animikian System.—The Animikian rocks (Whitewater series) consist of about 1,500 to 9,500 feet of quartzite, black slate, and in places iron-containing rocks which rest unconformably on the eroded surface of the Huronian and older rocks that have been described. The unconformity at the base of the Animikian points to general uplift of the land accompanied by widespread erosion. In most places the Animikian rocks are very little disturbed and have suffered almost no metamorphism. They are the youngest Proterozoic sedimentary rocks in the Timiskaming region.

Late Proterozoic Igneous Intrusions (Killarney Granite).—In the country to the west and south, around Lake Superior, there is a pre-Cambrian system of great thickness (Keweenawan) which is younger than the Animikian. Because this Late Proterozoic time was especially marked by igneous activity it is probable that intrusions of similar igneous rock in the Timiskaming region, intersecting Animikian and

older rocks, may be of Keweenawan age. These igneous intrusions (diabase, norite, etc.) are responsible for some of the great metalliferous deposits in this part of Canada, as the nickel-copper of the Sudbury district and the rich silver veins of the Cobalt area. In addition to the dark-colored rocks associated with these metallic deposits, there are great intrusions of still younger granite, called the *Killarney granite*, which cut through and extensively affect the Huronian rocks, especially in the southeast part of this region.

The Lake Superior Region

The Proterozoic formations of the Lake Superior region have been divided into four systems that are separated from one another by unconformities. The systems are named, in upward order, Lower Huronian, Middle Huronian, Upper Huronian (Animikian), and Keweenawan.

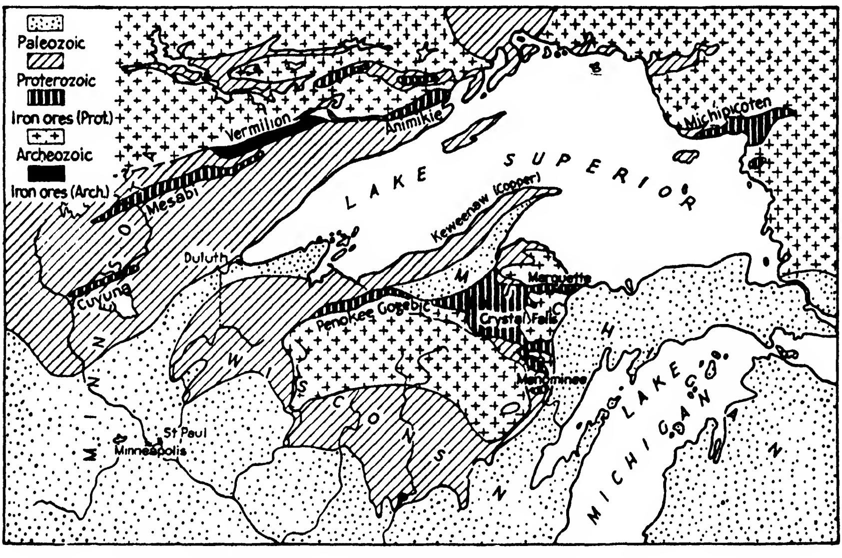


FIG. 39.—Map of Lake Superior district showing chief iron and copper districts.

Not all of these four are present in all parts of the Lake Superior region. There is doubt as to the exact relationships of some of the rocks called Huronian in the Lake Superior country to those of the type region north of Lake Huron, but some formations of the two regions are correlated fairly definitely (for example, Mesnard quartzite and Mona dolomite of the Lake Superior Lower Huronian with the Mississagi quartzite and Bruce limestone of the Lake Huron Bruce series). The "Lower and Middle Huronian" of the Lake Superior region probably corresponds to the type Huronian of the Timiskaming region, while equivalents of the Timiskaming beds are possibly found in the so-called Knife Lake series of the western Proterozoic area. On the other hand, the Knife Lake beds

have been correlated also with the Lower-Middle Huronian. The rocks called Upper Huronian or Animikian around Lake Superior are thought to correspond to those termed Animikian in the Canadian area. The thick series of Keweenawan sedimentary and volcanic rocks, which is found along the shores of Lake Superior, is apparently not represented in the Timiskaming country except by certain intrusive rocks. In general, the Huronian rocks are characterized by prevailing gray and green colors, by evidence of deposition in extensive water bodies, and by alteration due to metamorphic agencies; the Keweenawan, on the other hand, is conspicuously reddish in color, distinguished by prominence of stream-laid sediments, and little affected by metamorphism.

The Huronian Systems. *Lower Huronian System.*—The Lower Huronian rocks consist of conglomerate, quartzite, slate, and dolomite; locally there are iron-bearing strata and igneous rocks of various sorts. A long time of erosion preceded Lower Huronian sedimentation, and accordingly the base of this system is in contact with many different Archean rocks. The basal Huronian beds are commonly conglomeratic, with pebbles of granite, schist, and other Archean rocks. Some of these beds may be continental, but the majority of the Huronian sediments are probably marine.

Middle Huronian System.—Sedimentary deposits similar to those of the Lower Huronian compose the Middle Huronian system, but a widespread interruption in sedimentation is shown by the unconformity at its base. In places the older rocks were folded before the erosion which preceded the Middle Huronian time of rock formation. The sources of the Middle Huronian sediments consist not only of exposed Archean rocks but of parts of the Lower Huronian as well. Iron-bearing formations are very much more important in the Middle Huronian than in the lower system; it is from the Middle Huronian that by far the greater part of the commercial iron ore of the Lake Superior region is derived.

Upper Huronian (Animikian) System.—Quartzite, slate, and iron formations, with basic volcanic rocks in some places, compose the Upper Huronian or Animikian system. Slate is the most important kind of rock, and it is the thickest and most extensive of the Huronian deposits in the Lake Superior region. Most of the slate is apparently of deltaic origin. The Upper Huronian rests unconformably on Middle or Lower Huronian or occurs directly on the Archean. The unconformity at the base furnishes record of the time of erosion which intervened between this system and the one preceding. Erosion of adjacent unsubmerged lands during Animikian time supplied the sediments, which means that the source of the materials was any of the exposed older formations. Locally there are sills and flows of basic igneous rocks, and in a few places there are granitic intrusions.

Iron Ore.—A remarkable feature in the geologic history of the Lake Superior region is the formation of tremendous quantities of iron-bearing rocks. The iron formations have an aggregate thickness totaling several hundreds of feet and they originally covered many thousands of square miles. The iron, probably derived from the iron-rich igneous rocks that were brought to the surface during Proterozoic time, was carried in solution in the water bodies where the formations accumulated. It was precipitated chemically or through the agency of bacteria as iron silicate or iron carbonate. Subsequently, but before Paleozoic time, oxidation of these compounds changed them to cherty hematite and similar very

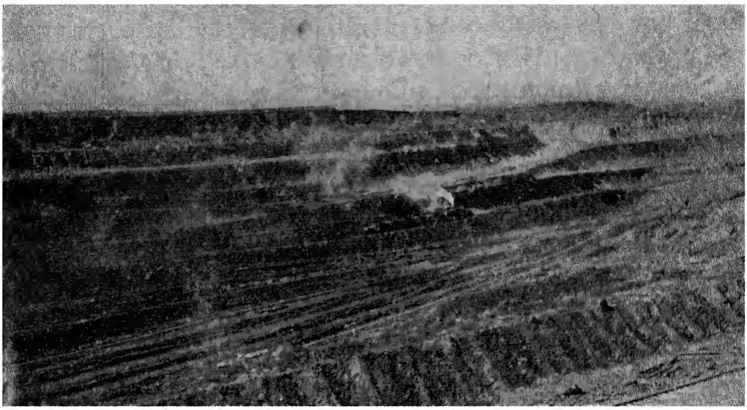


Fig. 40.—Open-pit iron mine in the Mesabi district, near Hibbing, Minn. (*R. T. Chamberlin, from Chamberlin and Salisbury, Historical Geology, Henry Holt & Company.*)

ferruginous, siliceous rock. Along outcrops of the iron formations, which are narrow and elongate because of steep folding, ground water has slowly dissolved away the siliceous impurities, leaving the iron oxide behind. The iron has thus accumulated as a residue and is sufficiently concentrated in several districts to form a high-grade ore. The work of solution has rendered the ore in many places so soft that it can be mined with steam shovels and loaded directly in cars that are run into great open pits.

The Lake Superior region produces about 85 per cent of the iron ore of the United States. Iron mining began in the Marquette district of Michigan in 1848. Other important districts are the Menominee, opened in 1872, Crystal Falls and Iron River (1880), Gogebic (1884), Vermilion (1885), Mesabi (1891), and Cuyuna (1903). Most of the iron-bearing formations are of Huronian age, but those of the Vermilion district are Archean. More than 1,500 million tons of iron ore have been produced in the Lake Superior region.

Thickness of Formations.—The thickness of formations in the Huronian of the Lake Superior country changes from place to place and because

of deformation of the rocks and extensive cover by glacial drift exact measurements are often difficult to make. The total thickness of the Huronian systems in most parts of the region ranges from about 4,000 to 9,000 feet, but in the Gogebic district of northern Wisconsin the thickness may be 12,000 to 15,000 feet. The accumulation of this great thickness, including some types of rock that probably were formed only very slowly, indicates that this part of Proterozoic time was extremely long, and there is, of course, no measure of the time represented by the unconformities that separate the systems.

Folding and Intrusion.—The Lower Huronian rocks were folded, and were intruded by batholithic masses of granite, and then were beveled by the erosion that preceded Middle Huronian deposition. The Middle Huronian in turn shows in some places folding and intrusion by igneous rocks which affected it and the preceding systems but came before the Upper Huronian. Again, the Upper Huronian is cut by still younger granites, which belong to the closing part of Proterozoic time or are not determined exactly as to age.

Keweenawan System. *Distribution and General Character.*—On the south side of Lake Superior in northern Michigan, where Keweenaw Peninsula projects like a thumb toward the center of the lake, and in some other parts of the Lake Superior region, is a great thickness of strata that have been called the Keweenawan system. These beds, consisting mainly of lava flows and intrusive sills or laccoliths in the lower part, rest unconformably on Animikian to Archean rocks and occur unconformably beneath the Cambrian. The igneous rocks are mostly dark-colored and basaltic in character. In the lower part of the series one lava flow rests directly on another or is separated only by a thin deposit of sand and gravel, which shows that not very much time elapsed between successive flows. North of Lake Superior, however, in the Nipigon region, there is a considerable thickness of sediments, including limestones, at the base of the Keweenawan system.

Higher in the Keweenawan system the proportion of sedimentary rock increases and there was evidently a correspondingly longer interval between the volcanic eruptions. The uppermost part of the system consists almost entirely of reddish-brown, yellowish, and purplish sandstones and conglomerates of nonmarine origin, without intervening lava flows. These sedimentary rocks were largely derived from disintegration of the older Keweenawan lava flows and other Proterozoic rocks of the region. They appear to have been deposited under semiarid conditions.

The Lower Keweenawan rocks are commonly tilted and truncated by erosion, the unconformity at the base of the Cambrian being strongly defined; the Upper Keweenawan, however, lies nearly if not quite parallel to overlying Cambrian sandstones. Since the known Cambrian of the

Lake Superior region belongs entirely to the upper part of that system, it is possible that some of the Late Keweenawan beds may actually be equivalent in age to Middle or Lower Cambrian deposits elsewhere, but no fossils have been found in the Keweenawan to substantiate this.

Thickness.—The Keweenawan rocks are very thick, measuring as much as 15,000 feet in many places. In parts of northern Wisconsin and Michigan the total thickness has been reported to be as much as 50,000 feet. It is certain that accumulation of successive sheets of lava could produce a very great thickness of rock in a relatively short period of geologic time if volcanic activity continued, and there are indications that the Keweenawan sediments were deposited rapidly. However, Keweenawan time surely represents several millions of years, and there must have been a general slow subsidence of the earth crust beneath the area of lava flows and sediments. It is possible that the larger thickness determinations cited are considerably too great, owing to (1) errors in field observations, including undetected changes in the dip of the rocks or duplication of beds by faulting, and (2) reckoning of apparent rather than actual thickness, if the layers have a shingled, foreset structure. On the other hand, it is possible that the Keweenawan rocks are as thick as they appear to be, in which case the earth crust beneath them must have subsided greatly, and about as rapidly as these late Proterozoic rocks were formed.

Igneous Activity.—The enormous igneous activity which is evidenced by the Keweenawan lava flows constitutes one of the major known records of vulcanism during earth history. The igneous action was not limited to surface extrusions, for in the country around the west end of Lake Superior is one of the largest single intrusive masses known (Duluth gabbro), having an original areal extent of approximately 15,000 square miles and an estimated thickness of several thousand feet. Like the Keweenawan flows, the intrusive mass is comparatively basic and is termed a gabbro. Other intrusions of granitic, batholithic nature (Killarneyan) appear to belong at the close of Keweenawan time. The kind of igneous rocks of Keweenawan age and the minerals in them are essentially the same in the Lake Superior and Timiskaming regions.

Copper.—The Keweenawan rocks of northern Michigan are especially noteworthy on account of the presence in them of enormous quantities of native copper. The copper occurs as fillings of small cavities in the lava rocks and in pore spaces between the pebbles of conglomerates (lode deposits), and as vein fillings along fractures (fissure deposits). The copper, like most metals that are mined, was derived originally from igneous magma, and it was deposited by solutions that probably came mainly from the great intrusion of gabbro. Mining of copper began in the Keweenaw district in 1844 and more than four million tons of metallic copper have been produced from it to date.

Killarneyan Revolution.—The intrusion of granite batholiths which cut rocks that are regarded as Keweenawan in age and the structural disturbance and metamorphism of the sedimentary rocks which are associated with these intrusions are indications of a crustal disturbance that affected much of the southern Canadian Shield. The rocks now seen in the more greatly disturbed areas represent merely the roots of a range of mountains, probably Late Keweenawan or post-Proterozoic in age, which extended southwestward from the Killarney region on the north side of the present Lake Huron to the country south of Lake

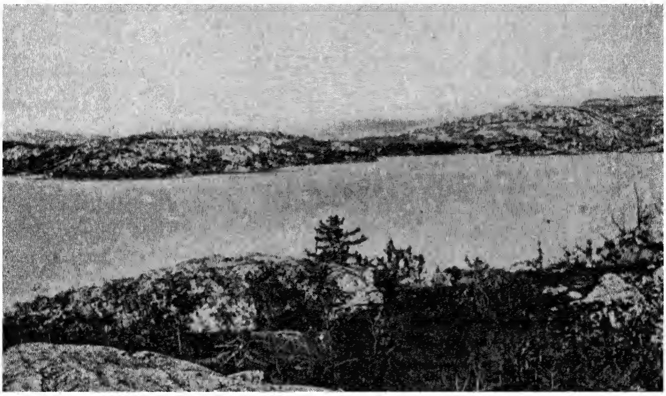


FIG. 41.—Hills of Killarney granite, Killarney Bay on the northeast shore of Lake Huron, in Ontario, Canada. (*Collins and Quirke, Geol. Survey Canada.*)

Superior, and possibly much farther southwest. The mountains perhaps reached also a long distance east of Lake Huron. This mountain-making movement has been named the Killarneyan revolution.

The Laurentian Region

Adjacent to the St. Lawrence River in Quebec, eastern Ontario, and northern New York are extensive exposures of sedimentary rocks, dominantly calcareous, called the Grenville series. They are intruded by granitic rocks that include the original "Laurentian." Recent studies in the region about Georgian Bay between the Laurentian and the Timiskaming districts indicate that part of the Grenville is equivalent to the Huronian. If this is true, it follows that the granite which intrudes the Grenville is younger than at least a part of the Huronian and probably corresponds to the Killarney granite which is regarded as Keweenawan in age.

PROTEROZOIC ROCKS OF OTHER REGIONS

Appalachian Region.—In the Piedmont region on the east side of the Appalachian Mountains, Proterozoic rocks are identified in many places,

but they appear to be more highly metamorphosed than in most parts of the southern Canadian Shield. The terrigenous or clastic sediments are largely altered to schist, and limestone beds are changed to marble. Only one Proterozoic system of rocks (Glen Arm) is identified, and to which of the systems in the Lake Superior-Huron country it corresponds cannot be determined definitely. Proterozoic deposits in southeastern Pennsylvania, Maryland, and Virginia are estimated to have a thickness of 8,000 to 10,000 feet; they consist dominantly of schist. Near the base are beds of marble and quartzite with interbedded volcanic rocks which become especially important toward the west. The Proterozoic rests unconformably on gneiss which is presumably of Archean age, and it is overlain unconformably by Lower Cambrian strata.

Farther south, in the Carolinas, Georgia, and Alabama, there is a huge thickness of schistose sediments (Talladega) that have been overthrust westward against Cambrian and Lower Paleozoic rocks. They are probably in part of Proterozoic age, but their structure is so complex that it is difficult to determine very much about them. Certainly there was very great deposition of sand, silt, clay, and some limestone in this part of the continent early in geologic history.

It is possible that the 12,000 feet or more of quartzites, conglomerates, and dark slaty shales, collectively known as the Ocoee beds, which occur in eastern Tennessee, western North Carolina, and northwestern Georgia, are Late Proterozoic in age. These rocks are described in the chapter on the Cambrian.

Rocky Mountain Region.—Very thick series of sedimentary rocks that rest unconformably on granites and gneisses of probable Archean age and that are overlain unconformably by Cambrian or younger rocks occur in parts of the Rocky Mountain region. These have been studied and described in parts of Colorado and Wyoming, but especially in Montana, Idaho, Alberta, and British Columbia. In the latter region the Proterozoic rocks, known as the Belt series, have an estimated thickness of approximately 30,000 feet. In this series, which is probably of Keweenawan age, there are limestone beds totaling thousands of feet in thickness, but the main part of the section is composed of quartzite and argillite (hard, dense clay rock). The sediments become thicker and coarser toward the west, indicating that their source lay in this direction. There are abundant ripple marks, mud cracks, and cross-bedding, which prove that the sediments were deposited in shallow water. A noteworthy fact concerning the Belt series is that much of it is almost horizontal. Although there has been uplift amounting to thousands of feet during subsequent geologic times and although parts of the Proterozoic rocks have been shoved laterally a distance of several miles and thrust-faulted on to very much younger strata, the Proterozoic beds of the Glacier National Park region are surprisingly little folded.

The Needle Mountains of southwestern Colorado contain large exposures of a tremendously thick series of quartzites of Proterozoic age which have been profoundly folded. The folds were smoothly beveled by erosion before deposition of Cambrian beds. In places one may see horizontal Paleozoic rocks resting on vertical Proterozoic strata.

Grand Canyon Region.—The exposures of Proterozoic rocks in the Grand Canyon, already noted, are interesting because of the great bare rock exposures which make so plain the nature of the succession of these rocks and their relation to the Archean and the Paleozoic formations.

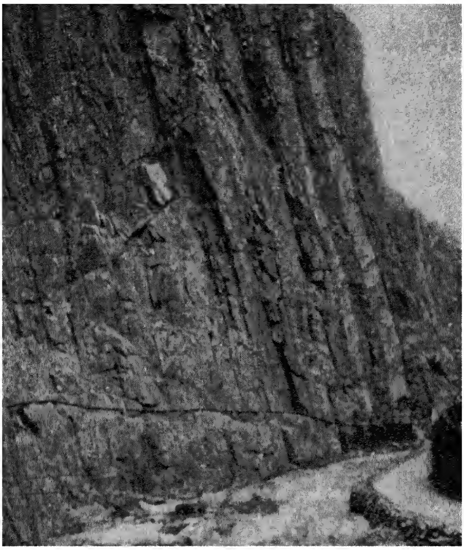


Fig. 42.—Vertical beds of Proterozoic quartzite in Thompson Canyon, east of Rocky Mountain National Park, Colorado. (*W. T. Lee, U. S. Geol. Survey.*)

The presence of limestone, shale, and quartzite, and of red beds with ripple marks and mud cracks, indicates the very wide variety of conditions of sedimentation that existed during Proterozoic time in this region. Both marine and nonmarine conditions appear to be represented. In addition, there are great thicknesses of igneous rocks, both intrusive and extrusive.

Europe.—Proterozoic rocks are well-known in different parts of Europe but are best exposed and have been most studied in Scotland and in northern Sweden and Finland. In northwestern Scotland the Proterozoic consists of a moderately thick series of quartzitic sandstone, probably of Keweenawan age, which rests unconformably on a complex of gneisses, granites, quartzites, iron formations, and other rocks, which may be of Huronian age.

Finland and northern Sweden contain a succession of at least three great sedimentary systems of Proterozoic age accompanied by igneous intrusions and extrusions. On the whole, these are comparable to the rock systems observed in southern Canada, the oldest being much metamorphosed and the youngest comparatively little altered.

Other Continents.—Extensive exposures of Proterozoic rocks representing three distinct systems have been identified in Mongolia and China. Rocks of this age are also recognized in Australia, India, and Africa. In Brazil there are enormous deposits of nearly pure iron ore which was deposited in its present state as a sedimentary formation. The ores and some of the associated rocks are regarded as Proterozoic in age.

Glacial deposits that belong to either the closing part of Proterozoic time or very early Cambrian occur in southern Australia, China, and Norway. They are evidently associated with the time of continental elevation that is so widely marked by the sub-Cambrian unconformity.

OUTLINE OF PROTEROZOIC PHYSICAL HISTORY

The characters and thickness of the Proterozoic sedimentary formations, their structure and conformable or unconformable relations to one another and to older and younger rock systems, and the nature and structural relations of igneous rocks that occur are the elements on which the physical history of this geologic era is interpreted. The succession of events in Proterozoic history as indicated by the most complete available record may be reviewed briefly in order.

Post-Archeozoic Erosion.—(1) The great unconformity at the base of the Proterozoic rocks shows that the Archean lands were eroded for a very long time until the country was a practically featureless plain. Where the materials eroded at this time were deposited is not known.

Timiskaming (Pre-Huronian) Period.—(2) A depression or submergence of the Archean lands permitted the early Proterozoic sea to cover the region, and beds of sediment called Timiskaming began to accumulate. (3) After a long period of deposition the earth crust was disturbed, the Timiskaming sediments being folded and faulted and in places intruded by granitic rocks. Mountains resulted from these disturbances. (4) The elevated lands were eroded and eventually reduced to a lowland plain. This is indicated by the unconformity at the base of the Huronian sediments.

Lower Huronian Period.—(5) Deposition of gravel, sand, and silt occurred in the Great Lakes region and probably elsewhere when the sea readvanced over the country, forming the Lower Huronian (Bruce) deposits. (6) The land was somewhat upraised again or the sea withdrawn so that previously deposited sediments were eroded, as shown by the unconformity between the Lower and Middle Huronian.

Middle Huronian Period.—(7) Glacial deposits at the base of the Middle Huronian (Cobalt) show that climatic conditions were such for a time as to produce widespread glaciation in part of North America. This was followed by accumulation of a thick series of sedimentary rocks. (8) Again there was elevation of the land accompanied in places by folding of the previously formed rocks and consequent erosion.

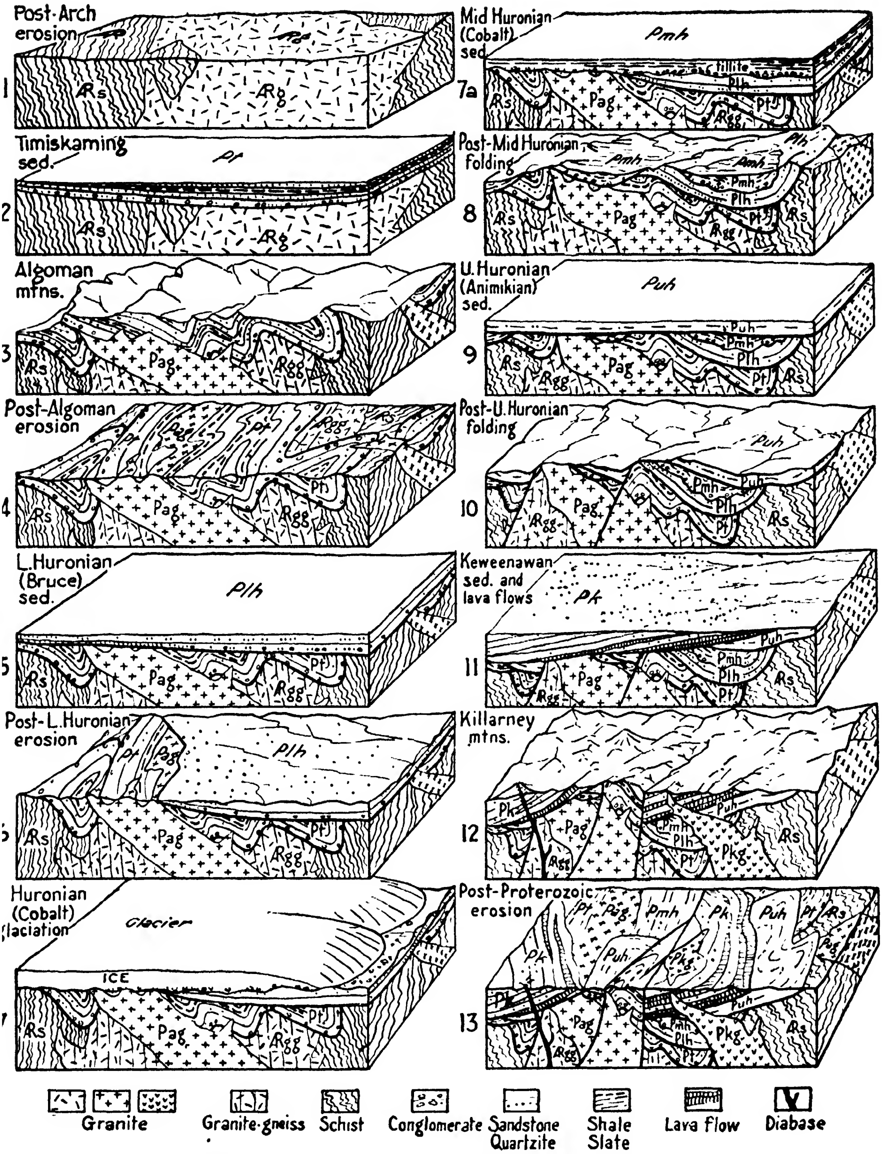


FIG. 43.—Block diagrams illustrating successive stages in the physical history of the Canadian Shield region in pre-Cambrian time.

Explanation of symbols: *ARs*, Archean schist; *ARg*, Archean granite; *ARgg*, Archean granite gneiss; *Pt*, Proterozoic, Timiskaming beds; *Pag*, Proterozoic, Algoman granite; *Plh*, Proterozoic, Lower Huronian beds; *Pmh*, Proterozoic, Middle Huronian beds; *Puh*, Proterozoic, Upper Huronian beds; *Pk*, Proterozoic, Keweenawan beds; *Pkg*, Proterozoic, Killarney granite.

Upper Huronian (Animikian) Period.—(9) When the sea readvanced upon the Canadian Shield, very important deposits of iron-bearing beds were formed in it. The thickness of these rocks indicates a long period of deposition. (10) Deformation accompanied by emergence and erosion followed this epoch of sedimentation.

Keweenawan Period.—(11) Enormous lava flows with gradually increasing amounts of sand deposition were accompanied by slow subsidence of parts of the earth crust until a very great thickness of rock was formed. (12) Intrusion of basic and of granitic igneous rocks on a large scale, and in places the considerable deformation of previously accumu-

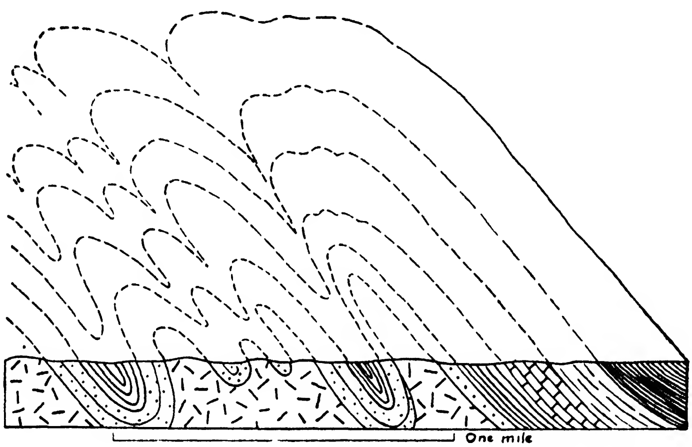


Fig. 44.—Section of pre-Cambrian rocks in the Marquette district of northern Michigan, with reconstructed folds. This drawing suggests something of the magnitude of the erosion that has occurred. The region is peneplaned.

lated rocks, terminated sedimentation and produced mountains. (13) Widespread and very prolonged erosion reduced the uplands to a nearly featureless plain that is represented in the unconformity at the base of the Cambrian. This brought the Proterozoic era to a close. Glaciation occurred during the time of general land elevation at the end of the Proterozoic and beginning of the Paleozoic.

SUMMARY

The Proterozoic sequence of rocks overlies the Archean unconformably and is in turn overlain unconformably by Paleozoic or younger strata. The dominant types of Proterozoic sedimentary rocks are quartzite, slate, dolomite, and iron formation, the combined thickness of which measures many thousands of feet; there are also conglomerates and glacial tillite beds. Dark-colored lava sheets and basic intrusive igneous rocks and light-colored granites are important in many places. The structure of the Proterozoic rocks is generally much simpler than that of the Archean

and the order of succession of rock formations can be determined much more completely.

The chief areas of Proterozoic outcrops are located in the southern part of the Canadian Shield. The most complete succession of sedimentary deposits and igneous rocks is found in (1) the Timiskaming region north of Lake Huron, and (2) the Lake Superior region. Classification of the Proterozoic rocks and the most detailed record of history in this era are drawn from these regions.

The chief stratigraphic divisions and a summary of geologic history based on lithologic and structural characters shown by them are given in the preceding section.

Proterozoic rocks are recognized in the Appalachians, scattered parts of the Continental Interior, the Rockies, and in states farther west. They are found also in each of the other continents, the general character of the rocks and physical history corresponding approximately to those of North America.

Glaciation in mid-Proterozoic time is clearly evidenced, and there are also glacial deposits in several parts of the world belonging to the time of land elevation at the close of the Proterozoic.

Rich deposits of iron and copper, especially in the Lake Superior region, occur in Proterozoic rocks; there are also nickel and some other metals.

CHAPTER IX

THE BEGINNING OF LIFE

The inception of life on the earth is an event that seems to us hardly second in importance to the birth of the planet itself. A lifeless earth would interest us not at all, for we ourselves should then have no existence. Indeed, it is hardly too much to say that the beginning of life and its subsequent development into the many hundred thousand kinds of extinct and living plants and animals of the earth offer a story even more wonderful than that of the origin and evolution of the physical universe.

But how, and when, did life appear on the earth? What was the nature of the earliest life forms? Is geologic evidence bearing on these questions to be found?

THE ORIGIN OF LIFE

Two views that are at least partially opposed to one another may be advanced concerning the origin of life. (1) Life is the result of special creation; the existence of plants and animals on the earth depends on the creative act of a Deity. (2) Life is the result of certain physicochemical conditions; the introduction of these conditions and the properties of matter that are involved depend on "laws" of nature, which in turn are an expression of inherent characters of the universe. All of these are conceivably the result of an initial divinely established order; otherwise there is no understandable beginning or end.

Result of Special Creation.—If the beginning of life on the earth is the result of special creation, geologic and biologic evidence strongly supports the conclusion that the multitudinous variety of later organisms is the result of gradual differentiation, or, in other words, of evolution. The testimony of several entirely independent lines of study (embryology, comparative anatomy, paleontology, blood tests, relationships shown by classification, geographic distribution, and organic changes controlled by domestication and experimentation) so uniformly and overwhelmingly supports the theory of evolution that there is not the slightest room for reasonable doubt as to the actuality of evolution of life. Probably the chief causes of this evolution are changes in physical environment and competition among organisms, but there is lack of agreement as to the biologic mechanism of evolutionary changes. We may say, then, that the hypothesis of origin of life by special creation can apply only to the beginning of life on the earth, not to the making of each different kind of later life.

Result of Certain Physicochemical Conditions.—Living matter is composed chiefly of carbon, hydrogen, and oxygen, with smaller amounts of nitrogen, sulphur, sodium, calcium, iron, phosphorus, etc. Chemical compounds that are essential to the existence of organisms are water and carbon dioxide. The elements in these compounds make practically all of the complicated substances produced by living beings. Sunlight supplies the energy necessary for chemical changes, and temperature must be within certain limits.

According to the view of most biologists, the sunlighted ocean waters offer most favorable conditions for the initiation of life, and here some of the most primitive forms of plant life abound. It is difficult, however, to see how cell structures could originate in this sort of fluid medium where solutions are very dilute and nearly in equilibrium.

Chamberlin has pointed out that the particular elements needed in the construction of living cells are found in meteorites (which are equivalent or comparable to planetesimals), and that these critical elements occur in forms (carbides, hydrides, nitrides) that are unstable in the presence of the earth's atmosphere and hydrosphere. He suggests that the most favorable environment for initiation of living cells is moist porous sands or soils of the land where the atmosphere and hydrosphere, coming in contact with unstable planetesimal material, should produce chemical reactions like those in living cells; and the physical environment is favorable to the making of cells. But in any case there remains to be explained how the cells, if thus formed, come to propagate new cells, and these still others; self-reproduction is one of the outstanding properties of living organisms.

The fact that material showing the properties of living cells has not been synthesized in the laboratory, and lack of observed "spontaneous" development of life out of purely inorganic matter, may be urged against the hypotheses of the beginning of life in exclusive physicochemical conditions. The special conditions postulated by Chamberlin differ materially from moist porous parts of the lithosphere in later geologic time, and conceivably this might account for lack of evidence of the generation of life from inorganic sources at the present time.

The discovery of the so-called filterable viruses which cause various diseases in plants and animals has possible bearing on the beginning of life. The active agency of the viruses consists of particles too small for microscopic observation; they are of colloidal size and pass through the openings of the finest porcelain filters. If the virus particles are living, as indicated by some lines of evidence, it is suggested that aggregates of a comparatively small number of certain molecules may possess properties of living matter and that such an organization of molecules may be very much less complex than a cell. Indeed, a one-celled organism, which has been presumed to be the simplest kind of life, may belong very far

along in the scale of evolution. And this suggests both more extreme antiquity of life in the Archeozoic era and the possibility that under proper physicochemical conditions life may have "begun" on the earth many, many times. The latter suggestion affords basis for a hypothesis of the polyphyletic origin of unicellular life and its various derivatives. The subject is too speculative, however, to merit further consideration.

LIFE OF THE ARCHEOZOIC ERA

The conclusion that life began on the earth during the Archeozoic era rests on two main lines of evidence. One is the advanced development and indication of great antiquity of the earliest known well-preserved fossils found in the lower Paleozoic rocks. The differentiation of one kind of organism from another is undoubtedly a very slow, gradual process and the time involved in the founding of the various types of plants and specialized animals that are known in the Cambrian must surely be measured in many millions of years. This implies, then, that the beginning of life must reach very far back into the pre-Cambrian eras.

The other evidence is the considerable quantity of carbonaceous material, iron deposits, and sedimentary limestones in Archean rocks. Each of these are formed through the agency of life, but their presence does not of itself prove absolutely the existence of life because it is possible to make them inorganically. However, the mode of occurrence of the carbon, as graphite particles and lenses in sedimentary rocks, strongly favors an organic origin, the alteration to graphite being due to metamorphism. Evidences of fossil bacteria have been recorded from iron formations of Proterozoic age and it is reasonable to suppose that Archean iron-bearing rocks may likewise owe existence to iron-depositing bacteria.

The fact that deposits of sedimentary origin are among the oldest known on the earth's surface, and that these exhibit no essential marks of an environment at the time of their accumulation different from later history, implies that physical conditions were favorable to life in Archeozoic time. Further, as noted by Chamberlin and Salisbury, the normal operation of atmospheric agencies, such as oxidation which is indicated in the making of Archean sediments, argues the existence of abundant though possibly primitive plant life, for plants are the chief source of free oxygen in the air.

General unfitness for preservation may be assumed in the case of the early plants and animals, but, in addition to this, the extreme metamorphism to which most of the oldest rocks have been subjected would readily account for absence of fossils even if they had originally been present. The time when life appeared and the existence and the nature of life in the first era are therefore based on inference.

LIFE OF THE PROTEROZOIC ERA

The Proterozoic rocks afford not only indirect evidences of the presence of life but also definite remains or traces of plants and animals.

Bacteria.—The conclusion that iron deposits in northern Michigan are at least partly due to the action of bacteria has been strengthened greatly by recent discoveries (Gruner) of these exceedingly minute organisms in Lower Proterozoic rocks containing the iron deposits. It is

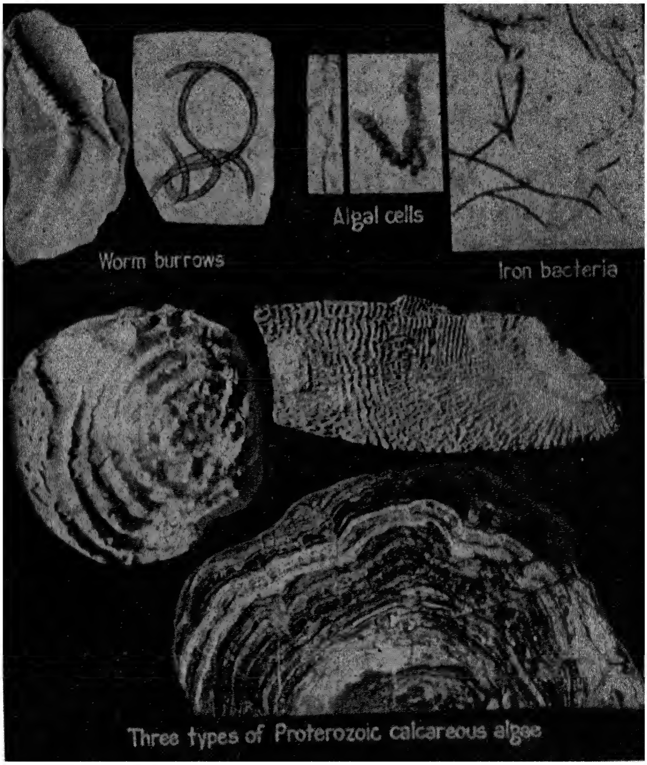


FIG. 45.—Some types of organic remains from Proterozoic formations.

not surprising that they have long been overlooked, since magnifications of five-hundred to one thousand times are necessary to detect their presence and character. Some of the fossils observed are slender, irregularly curved threads; others are branching and closely resemble certain living blue-green algae.

Lime-secreting Algae.—Quite different is the group of fossils supposed to be lime-secreting algae or seaweeds that occurs most abundantly in parts of the later Proterozoic rocks, especially in the Belt series of the northern Rockies. They are distributed over at least 6,000 square miles of territory and occur through a vertical range of thousands of feet.

Recently, good specimens have been obtained from near the base of the Proterozoic rock section in the Grand Canyon. Organic structure is indicated by the radiating and concentric arrangement of the material in these variously shaped masses which resemble the limy growths built by calcareous algae. The structure is not the same, however, as in known living higher algae. Many of these supposed algae grew singly, attaining a thickness and diameter of several inches, but more commonly they grew in widely extending beds and in some cases built up great masses or "reefs" of limestone. They probably thrived in moderately shallow, warm clear water. Whether the areas of algal growth were covered by fresh or salt water is not known.

Animal Remains.—The remaining known fossils of Proterozoic age consist of trails or burrows in sandy mud sediments, evidently made by animals, probably worms, and of a few poorly preserved shells representing primitive brachiopods or gastropods, and possibly some crustacean fragments. Altogether, evidence of animal life is pitifully meager. This is surprising and disappointing, since many of the later Proterozoic formations are almost undisturbed and are certainly less altered than the folded Paleozoic rocks in some areas that yield abundant fossils. Reasons for the general absence of fossils may lie partly in lack of development in Proterozoic time of structures suitable for fossilization, and perhaps, if life originated in the seas and subsequently became adapted to the lands, the Proterozoic strata might lack abundant organic remains if, as believed by some geologists, they are mainly nonmarine.

SUMMARY

The origin of life on the earth is one of the most important events of early geologic history, but there is no definite information concerning it. If the beginning of life was the result of special creation, there is overwhelming evidence, nevertheless, that the multitudinous kinds of subsequent life are the product of evolution. It seems probable that life originated as a result of certain physicochemical conditions, but this has not been proved and living matter has not been artificially synthesized.

The existence of life in the Archeozoic era rests on indirect evidence, consisting chiefly of the occurrence of carbonaceous deposits, iron formations, and limestones, all of which are commonly but not necessarily made by action of organisms. The very great advancement and specialization of life that are seen in the oldest fairly fossiliferous rocks (Cambrian) argues an exceedingly long antecedent development.

The Proterozoic rocks are mostly lacking in fossils but there are thick limestones in which lime-secreting algae of various sorts are common. The existence of fossil bacteria in Proterozoic rocks has recently been reported. Worm burrows and a few invertebrates show the presence of animals.

THE PALEOZOIC ERA

AGE OF ANCIENT LIFE

CHAPTER X

THE PALEOZOIC FORMATIONS

The rock formations that were made in Paleozoic time, the era of ancient life, are now exposed over a large part of North America and the other continents. Knowledge of Paleozoic history is based on study of the nature, distribution, and structure of these rocks, on their relations to one another, and on the remains of life contained in them. Before we review in any detail the evidences from which we may construct a picture of the physical conditions and the life of this era and determine at least the salient geologic events of Paleozoic time, it is desirable to survey the field in a broad way.

Definition of Paleozoic.—It has been pointed out that the major divisions of geologic time are established on the basis of the most important interruptions of sedimentation on the continents and by corresponding important breaks or times of accelerated change in the record of life. The Paleozoic era is clearly defined both by the occurrence of more or less prolonged "lost intervals" preceding and following it, and by distinctive characters of its fossil plant and animal life.

At the base of the great succession of rock strata that was formed during this time is the extremely widespread sub-Cambrian unconformity that marks profound erosion of the older rocks. This unconformity separates the rocks below that are practically devoid of fossils, from those above that in many places contain abundant remains of life; in most places it divides igneous or metamorphic rocks of crystalline texture and complex structure, from little-altered sedimentary rocks.

The upper boundary of the Paleozoic rocks is not so strikingly defined as the lower, for the rocks of the succeeding Mesozoic era are not greatly unlike those of Paleozoic age. There is, however, a widespread unconformity at this horizon and the change in the character of the fossils is well marked. In eastern and parts of south central North America where the Paleozoic rocks are highly deformed, the succeeding Mesozoic strata are nearly horizontal or only moderately tilted.

PALEOZOIC ROCKS IN NORTH AMERICA

Distribution

Areas of Surface Exposure.—Inspection of a geologic map of North America shows that rocks of Paleozoic age form the surface of a very

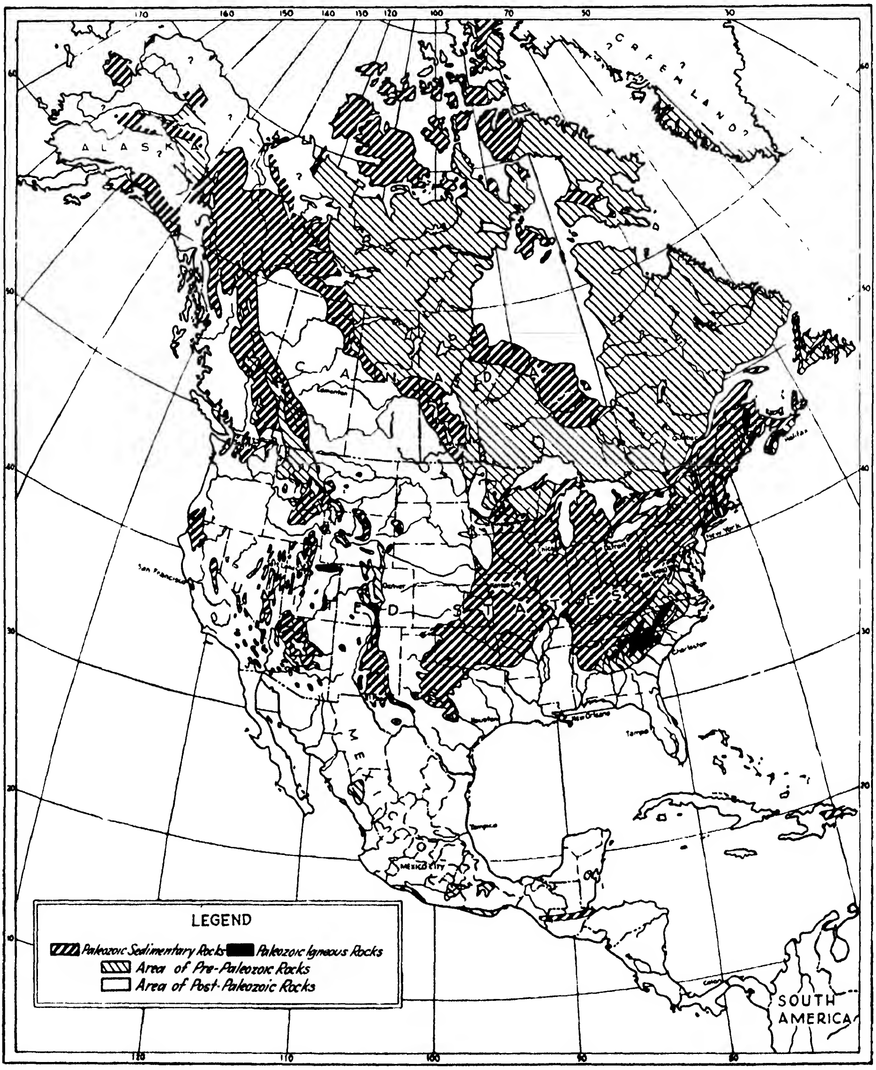


FIG. 46.—Map showing distribution of Paleozoic outcrop areas in North America.

large area, chiefly in the central and eastern parts of the continent (Fig. 46). Ignoring various unconsolidated surficial deposits of geologically recent origin, it is seen that one might travel continuously on Paleozoic formations from Texas to Nova Scotia, or from Minnesota to Alabama.

The region of Paleozoic outcrops comprises most of the plains country of the Mississippi Valley and the Great Lakes district, the rugged Appalachian Plateaus, the Appalachian Mountains, much of New England, and part of the maritime provinces of Canada. In addition, there are large exposures of Paleozoic rocks in western North America, chiefly in the Rocky Mountains, Colorado Plateau, Great Basin, northwestern Canada, and Alaska. Outcrops occur also on the shore of Hudson Bay, in the Arctic Archipelago, and in northern Greenland. Altogether about 35 per cent of the surface of the continent consists of Paleozoic formations or shows the presence of Paleozoic bedrock beneath relatively thin unconsolidated deposits. The outcrop area of these rocks includes a great agricultural and industrial region where approximately one-half of the population of the continent lives. Many lines of human activity are influenced very importantly by the physical character, topographic expression, and economic resources of the Paleozoic rocks.

Original Distribution.—The original area occupied by Paleozoic formations is certainly much larger than that of the present outcrops. We observe that in most places where younger strata adjoin the Paleozoic rocks the older formations disappear beneath the younger. Also, we find that in the outcrop area of post-Paleozoic beds there are many borings that penetrate Paleozoic deposits. It is definitely known that Paleozoic strata underlie most of the plains country east of the Rockies, where Mesozoic and Cenozoic rocks form much of the surface. To the territory of surface exposure we may therefore add a large but in part unknown area in which the Paleozoic rocks are concealed by younger sediments. Furthermore, it is apparent in certain districts that erosion has removed the Paleozoic rocks from an indefinitely large area. The thickness and other characters of the Paleozoic formations bordering the pre-Cambrian areas of the Canadian Shield, the Appalachians, the Rockies, and other mountains indicate that before the uplift and erosion of these areas the Paleozoic rocks covered much country where now they are stripped away. Outlying patches of marine Paleozoic strata resting on pre-Cambrian rocks of the Canadian Shield are at present separated by several hundreds of miles from the nearest corresponding formations, indicating that erosion has removed the formerly intervening connections.

General Character of Paleozoic Outcrop Areas

The regions in which the Paleozoic rocks are exposed will be described briefly.

Appalachian Mountains.—In a geologic sense, the Appalachian Mountain system reaches uninterruptedly from Newfoundland to Alabama, for the folding and faulting that gave birth to the mountain structure affect this entire eastern part of the continent. In New England and

eastern Canada the Paleozoic rocks are very much disturbed and partially metamorphosed, but farther south they are less strongly compressed.

The characteristic features of the Appalachian district consist of persistent high, narrow-topped, and even-crested ridges that separate correspondingly elongate, rather narrow valleys. In general, the ridges extend many miles in nearly straight lines, but in places they bend very sharply, forming long narrow loops and zigzags. The shape of the valleys depends on the plan of the confining ridges; some of them are symmetrically canoe-shaped. These topographic characters are controlled by the hardness and the structure of the rock formations, the upturned, steeply dipping hard rocks forming the ridges and the soft, easily eroded forma-

Fig. 47.—Even-crested Appalachian mountain ridges near Harrisburg, Penn. Susquehanna River here flows almost at right angles to the trend of the ridges. (*G. W. Stose, U. S. Geol. Survey.*)

tions making the valleys. The generally even tops of the ridges are remnants of a peneplain formed by long-continued erosion that planed down hard and soft rocks alike. This peneplanation must have followed the folding of the rock strata and also must have antedated the regional uplift which caused the streams to excavate the present valleys.

The easternmost persistent elevation is the Blue Ridge, known also in parts of Pennsylvania as South Mountain, and in Maryland including the Catoctin Ridges. These ridges are formed by hard rocks of pre-Cambrian age and by resistant Lower Cambrian sandstones and quartzites. In the Tennessee-North Carolina portion of the Appalachian chain, where the quartzites are excessively thick, we find the most rugged portion of the entire mountain system.

Paralleling the Blue Ridge on its western side is a persistent lowland, commonly known as the Appalachian Valley. Portions of it in Pennsylvania and Maryland are called the Cumberland Valley, in Virginia the Shenandoah Valley, and in Tennessee and southward the Tennessee and

Coosa Valleys. This great valley, or series of valleys, is due to the occurrence of thick Early Paleozoic limestone and interbedded shale in a belt that corresponds with the position of the valley. These are weak rocks as compared to the massive hard sandstones and quartzites that compose the ridges. Though many of the limestones are hard, they are soluble and have been attacked by weathering so that they stand even lower than the shale formations. The valleys furnish wide, fertile farm lands in a timber-clad region that is mostly too rough and rocky for agricultural use.

The main series of narrow but prominent mountain ridges lies on the west side of the great valley and extends from northeastern Pennsylvania

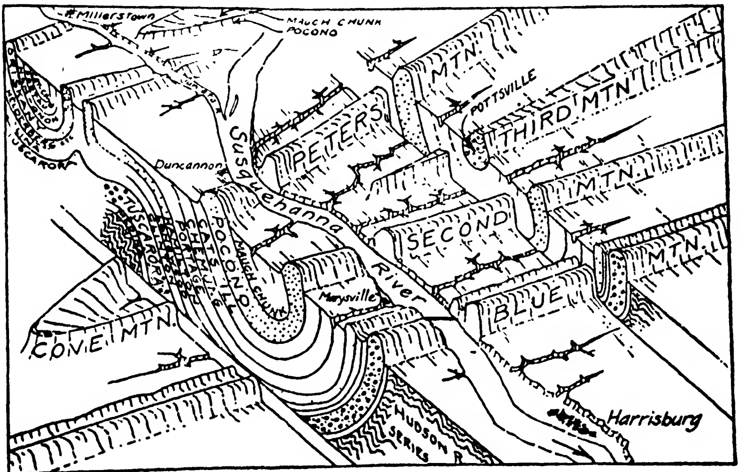


FIG. 48. - Diagram showing Appalachian ridges and valleys near Harrisburg, Penn., and the geologic structure associated with these topographic features. (*A. K. Lobeck, Block Diagrams, John Wiley & Sons, Inc.*)

to Alabama, covering a belt up to 60 miles or more in width. The most prominent ridge makers are hard sandstones; less prominent ones are cherty limestones. The valleys between the ridges are mainly carved in shale. Parts of the region can be reached only with much difficulty, for the steep-sided mountains, unbroken for dozens of miles, are barriers to travel that have very greatly affected man's activities in the region. Except for the "water-gap" and some "wind-gap" passageways made by certain rivers, where railroads, highways, and in some cases an electric line or canal are crowded closely together, the mountains would be a much greater barrier to travel.

A feature of special geologic interest in the mountain area is the considerable thickness of many of the rock formations and the very great total thickness of Paleozoic strata that is found here. Measurements in Alabama show that the Pottsville beds (Pennsylvanian) attain a thickness of 10,000 feet; the Catskill formation (Upper Devonian) in Pennsylvania,

4,700 feet; the Great Smoky quartzite (Lower Cambrian) in southeastern Tennessee, about 8,000 feet; and the entire Cambrian in Tennessee, approximately 18,000 feet. The thickness of the Paleozoic sediments is computed to be about 40,000 feet in southern Pennsylvania and Maryland, about 30,000 feet in Tennessee and Virginia, and about 38,000 feet in Alabama. These measurements, which indicate an accumulation of sediments totaling a maximum thickness of more than 7 miles, contrast greatly with measurements of the flat-lying Paleozoic rocks in the Great Lakes-Mississippi Valley region, where a thickness of a mile is rarely attained.

Appalachian Plateaus.—Bordering the mountains on the west is a rugged area of nearly flat-lying rocks that in New York, Pennsylvania,

Fig. 49.—A portion of the Appalachian Plateau country along New River, W. Va. The rock formations are nearly flat-lying. (*J. K. Hillers, U. S. Geol. Survey.*)

and southward to Kentucky is commonly known as the Allegheny Plateau, and in Tennessee and Alabama as the Cumberland Plateau. For the most part this area is intricately dissected by stream valleys, many of which are deep and much narrower than those in the Appalachian Mountains. There is a marked topographic difference, however, between the plateau and mountain areas, in that the ridges and valleys of the former, being uninfluenced by upturned hard and soft strata, are not straight and parallel but form a treelike pattern, as in most areas of flat or homogeneous rocks. Many of the streams have very crooked, meandering courses.

The surface rocks of the plateau country are mostly strata of Late Paleozoic age, including especially beds of the coal-bearing Pennsylvanian system. These rocks consist in large part of hard sandstone which serves to resist the attack of erosion and, therefore, to preserve the

plateau character of the region. The strata of older Paleozoic age are deeply buried. A well in northern West Virginia, starting in the lower part of the Pennsylvanian, penetrated rocks to a depth of 7,757 feet, ending in the Oriskany sandstone of Early Devonian age. Silurian, Ordovician, and Cambrian rocks lie still deeper.

Interior Plains.—On the northwest, the Appalachian Plateaus grade almost imperceptibly into the plains country of the Great Lakes and Mississippi Valley. The Paleozoic rocks of this region extend into Canada, occupying southern Ontario and surrounding all of the Great Lakes except Lake Superior. The northern limit of the Paleozoic formations in this region is determined by the extent to which erosion has stripped away rocks that once covered parts of the ancient crystallines of the Canadian Shield. Northwestward, the Paleozoic outcrops extend to Minnesota where they are overlapped by Late Mesozoic deposits that continue far to the west. The boundary between Paleozoic and younger rocks in the western part of the Interior Plains irregularly crosses northwestern Iowa, eastern Nebraska, and central Kansas to western Oklahoma and Texas. The Gulf Coastal Plains, which reach as far northward as southeastern Oklahoma and occupy most of the Mississippi Valley below the mouth of the Ohio, are composed of post-Paleozoic sediments, but, as in the western Great Plains, it is known that Paleozoic deposits underlie at least a part of this area.

The plains formed by the Paleozoic strata are intersected by numerous streams that have carved narrow to wide valleys, in places 300 feet or more in depth. Steep rocky bluffs occur along some of these streams, but in general the slopes of valley sides are rather gentle. Over a large area in Illinois, Indiana, and adjacent territory that has been made smooth by filling of glacial deposits, the surface is almost flat. In parts of the country west of the Mississippi River, as in Missouri, Kansas, Oklahoma, and Texas, there are prominent escarpments that are made by the outcrop of the more resistant Paleozoic formations. The strata of this region consist of shale, limestone, and sandstone which are important quantitatively in the order named. The shales are generally concealed by soil and vegetation; and since they tend to make gentle slopes and flats at the surface, outcrops of shale are not conspicuous. Limestone is exposed in bluffs along streams, in quarries, and at the edges of escarpments. Some of the limestone formations are thick and massive; others are thin but remarkably persistent. Sandstone is prominent only locally, although some Paleozoic sandstones are very widespread. Many of the formations contain prolific evidence of the existence of varied forms of life in Paleozoic time. Some beds, indeed, are literally made up of beautifully preserved fossils.

While the strata of the plains may be described in a broad sense as horizontal, they are actually slightly inclined in most places. Their dip

is generally less than 1 degree and is commonly recorded in terms of feet per mile. Most of the Paleozoic strata of the Great Lakes district slope gently toward central Michigan, forming a broad, saucer-like syncline. Accordingly, the youngest rocks occur here in the central part of the basin, surrounded concentrically by outcrops of the older formations. A wide dome-shaped uplift, its top south of Cincinnati (Cincinnati arch), is found in Kentucky, Ohio, and Indiana, and a smaller one (Nashville arch) occurs to the south, in Tennessee. Since structure and topography are not always related, the structurally highest part of a dome is not necessarily the highest in surface elevation. The Nashville arch, for

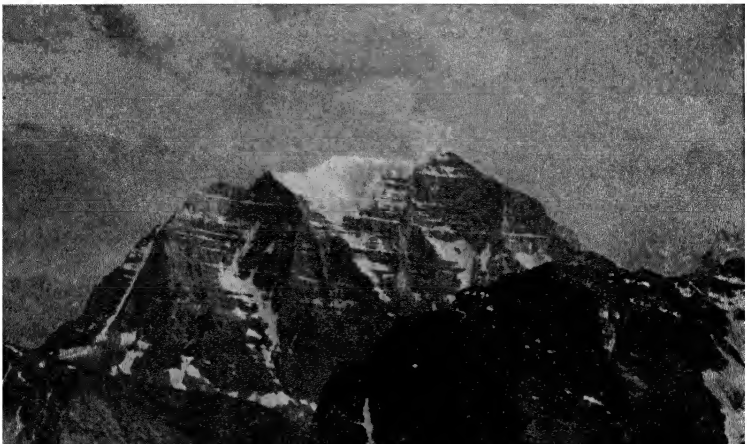


FIG. 50.—Paleozoic rocks, thousands of feet in thickness, occur in parts of the Rocky Mountain Cordillera. This view of Mount Temple, in the Canadian Rockies, shows over 5,000 feet of gently dipping Cambrian strata. (*R. T. Chamberlin, Chamberlin and Salisbury's Historical Geology, Henry Holt & Company.*)

example, is marked by a centrally located lowland area carved in older Paleozoic limestones. Surrounding this lowland is an upland, the Highland Rim, with a prominent inward-facing escarpment composed of younger Paleozoic rocks. The Ozark region of Missouri is a very broad, gentle, structural swell or dome. In all of these uplifts, older rocks are found at the surface, surrounded on all sides by outcrops of younger formations.

In the plains of the Mid-Continent region, stretching from Nebraska to northern Texas, the Paleozoic rocks dip gently westward, but on the east flank of the Rockies corresponding beds show a steep inclination eastward. The intervening area constitutes thus a structural sag in which the Paleozoic rocks are deeply buried by those of younger age.

Western North America.—Exposures of Paleozoic strata are found in various parts of Alaska, western Canada, and the western United States. Small areas of these rocks occur in northern and southern Mexico. The Alaskan Paleozoic formations, as yet not very well-known,

make up an important part of the Endicott Range in the northern part of that territory. Thick Paleozoic deposits are also present in eastern and southeastern Alaska. In western Canada, the Rockies and portions of the coastal mountains are mainly composed of Paleozoic strata, of which those found in the latter district are very much altered by metamorphism. Large areas of flat-lying Devonian beds occur east of the Rocky Mountains in northwestern Canada.

The Paleozoic formations of the western United States include the lower part of the sedimentary rocks upturned along the flanks of the Rockies in New Mexico and Colorado, around the Black Hills (South Dakota, Wyoming), the Bighorns and other mountains in Wyoming, Utah, and Montana. In eastern New Mexico, western Texas, and Arizona the Paleozoic strata are nearly horizontal and form plains and plateaus. The Grand Canyon is carved in upwarped Paleozoic and older rocks which form the Colorado Plateau in northern Arizona. The Great Basin country of western Utah, Nevada, and southeastern California contains many north-south trending mountain ranges that are largely made up of folded and faulted Paleozoic strata, in part of great thickness. The Sierra Nevadas and other mountains near the west coast are known to contain some highly altered Paleozoic sediments, although composed for the most part of rocks of later geologic age.

PALEOZOIC ROCKS IN OTHER CONTINENTS

Europe.—Paleozoic rocks are extensively exposed in Europe, especially in the northern and western parts of the continent. The topographic features and mineral resources (especially coal) of these Paleozoic areas have exerted a profound influence on man's activities.

In the *British Isles*, Paleozoic rocks occupy most of southern Scotland, northern and western England, and almost all of Wales and Ireland. The central part of Scotland is a lowland belt, the Scottish Lowlands, which extends to both the east and west coasts. It is made by weak rocks, most of which are Late Paleozoic in age and which include coal beds and oil-shale deposits. Here are all of the great cities of Scotland and over nine-tenths of the total population. The Lowlands are a great industrial district, whose growth has been dependent primarily on topography and mineral resources. South of the Lowlands are the southern Scotch Uplands, composed of more resistant Paleozoic rocks. This is a grassland country devoted mainly to sheep rearing. Important industrial centers are lacking. The upland slopes gently southward into the Pennine Range of northern England, which consists of a broad anticline of Paleozoic limestones and grits. On the east, south, and west this upland area is bordered by lowland belts of coal-bearing rocks, in which are located the great manufacturing centers of northern England. Wales and western England show an important, nearly complete series of Paleozoic rocks dipping gently eastward. Much of the early work leading to definition of the Paleozoic divisions was done on this section. Most of the rocks are marine and fossiliferous, but in the middle of the stratigraphic succession is the famous Old Red sandstone, which is of continental origin. Ireland consists of northern and southern highland areas, with an intermediate central plain. Upper Paleozoic limestones that produce a rich soil cover most of the region.

The *Scandinavian Peninsula* contains in its western and higher part a long belt of very complexly folded and faulted older Paleozoic rocks. These form part of the roots of the Caledonian Mountain chain, formed at the end of Silurian time.

Northern *Russia, Esthonia,* and *Poland* contain the largest uninterrupted areas of Paleozoic outcrops in Europe. The rocks here are comparable to those of the Mississippi Valley in the United States, in that they are of moderate thickness and are practically undisturbed by folding and faulting. Most of the Paleozoic divisions are well represented, and some formations are wonderfully fossiliferous.

The *Bohemian region* in central Europe is another important and famous region of Paleozoic outcrops, in which strata belonging especially to the older part of the era are well developed. These rocks contain abundant fine fossils.

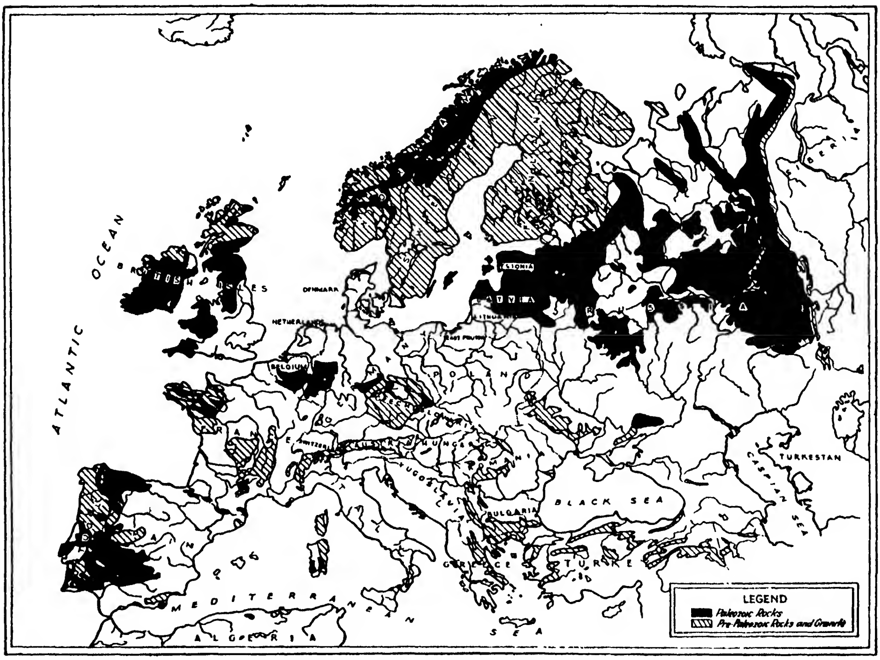


Fig. 51.—Map showing distribution of Paleozoic outcrop areas in Europe.

Western *Germany,* along the Rhine, southern *Belgium,* and northeastern *France* contain a Paleozoic area of complex structure that forms an upland, part of an ancient mountain chain that was formed across central Europe in Pennsylvanian time. It is bordered on the north and locally on the south by very important coal deposits, which have been an important factor in the economic development of this part of Europe and for possession of which wars have been waged.

Paleozoic rocks occur also in western and part of southern France, in the Pyrenees, in the western part of the Spanish Peninsula, and locally in Sardinia and Sicily.

Asia.—Paleozoic rocks representing the oldest to youngest divisions have been reported from various parts of Asia, especially in a belt extending from east to west across the southern part of the continent. Much detailed work, from which has come a long series of important reports, has been done by the British Government in India. The chief Paleozoic deposits are Pennsylvanian and Permian in age. Paleozoic rocks are well represented in China. They include especially very fossiliferous Cambrian and Pennsylvanian formations, study of which is important from the

standpoint of the relations of contained fossil life to that in North America. Paleozoic rocks occur also in Mongolia, Manchukuo, eastern Siberia, Japan, Korea, and the East Indies. The small island of Timor, in the last-named region, has yielded a large number of very interesting Late Paleozoic fossils, recently described in a series of memoirs.

Australia, especially in the eastern part, contains a fairly complete series of Paleozoic deposits which shows marked similarity and some interesting dissimilarities to rocks of this age in other parts of the world.

Africa contains widespread deposits belonging to the Paleozoic, but the formations in most places are neither very thick nor is the record very complete. The Sahara region in the northern part of the continent is partly floored by Middle Paleozoic sandstone, disintegration of which has helped to supply sand to the desert areas. A very thick series of Paleozoic beds occurs in South Africa. The deposits consist mostly of grits, sandstones, and shales, representing especially the later part of the era.

South America.—The northern and central parts of South America and islands off the southern tip contain Paleozoic rocks.

SUMMARY

Paleozoic rocks comprise the oldest abundantly fossiliferous strata. In most places great unconformities separate these rocks from those of earlier and later eras. Some of the formations were made on the land by streams and in lakes, but most of them consist of sediment deposited in shallow seas that invaded the continents.

Paleozoic outcrops cover much of eastern and central North America, and smaller areas in the western and northern parts of the continent. In New England and eastern Canada most of the Paleozoic rocks are highly deformed as well as invaded extensively by igneous rocks. The Appalachian Mountains are mainly composed of folded and faulted Paleozoic strata of great thickness, attaining in places a maximum thickness of 40,000 feet. The plains country of the Great Lakes and upper Mississippi Valley is made up of nearly flat-lying Paleozoic strata having a total thickness in most places of less than 5,000 feet. Gentle broad synclines, like the Michigan basin, and anticlines, like the Ozark and Cincinnati domes, characterize the structure of the Interior Plains country. In western North America the Paleozoic rocks crop out on the flanks of many of the mountain ranges, besides forming in places extensive plain and plateau areas.

The total distribution of Paleozoic strata is much greater than the area of surface exposure, for younger deposits cover them over thousands of square miles. Further, their original distribution must have included great areas in which subsequent erosion has removed them.

Rocks of Paleozoic age are found in each of the other continents.

THE EARLY PALEOZOIC SUBERA

CHAPTER XI

FORMATIONS AND PHYSICAL HISTORY OF CAMBRIAN TIME

The rocks called Cambrian include the oldest known sedimentary strata that contain more or less abundant well-preserved fossil remains. This does not mean that all strata of Cambrian age are fossiliferous; on the contrary, some formations are as barren of organic remains as the pre-Cambrian. Most of the Cambrian formations, however, yield some fossils and many beds contain great numbers of them.

The Cambrian rocks rest unconformably on pre-Cambrian formations which are mostly unfossiliferous and very different from the Cambrian in appearance. Because of the clearly defined and prominent nature of this unconformity, the base of the Cambrian is easily recognized. The top of the Cambrian is likewise defined by an unconformity or hiatus in the geologic record which, however, is very much less important than that at the base. The evidence of withdrawal of continental seas is especially found in a discontinuity of the fossil faunas (entire assemblage of animal life) contained in the rocks, older species disappearing suddenly, while many new kinds of animals are introduced in the next younger strata; however, there is also physical evidence.

As already noted, the Cambrian rocks were named nearly a century ago in Wales but the upper limits of the system have subsequently been revised and in the light of added information may still require some modification.

GENERAL NATURE AND DIVISIONS OF THE CAMBRIAN ROCKS

Variation in Cambrian Sedimentation.—Sedimentary deposits of Cambrian age consist of limestone, shale, sandstone, and conglomerate. The kind of rock may differ greatly in different parts of a single exposed section and it commonly differs from one region to another. This is entirely natural, for it is most likely that the nature of sediments deposited in a given place will change as surrounding conditions are altered, and that conditions in one place will have no similarity to those in another. Accordingly, the basal part of one section of Cambrian rocks may consist of conglomerate, a higher part of sandstone, and still higher parts of shale and limestone. This points to conditions that were of one sort in the early part of this time of deposition and to conditions of another sort

later on. Also, deposits of sandstone in one region may be contemporaneous with shale or limestone in another, which merely means that the one was formed near shore and the other at a greater distance from land, or there are several other possibilities. It is thus true of the Cambrian rocks that variation in kind of sediment occurs both stratigraphically, from one horizon in the section to another, and geographically, from one locality to another. As we might suppose, indeed, this generalization almost necessarily holds for the rocks of every geologic period.

On the other hand, kinds of rock and the conditions of sedimentation that they denote are not commonly extremely variable, either vertically

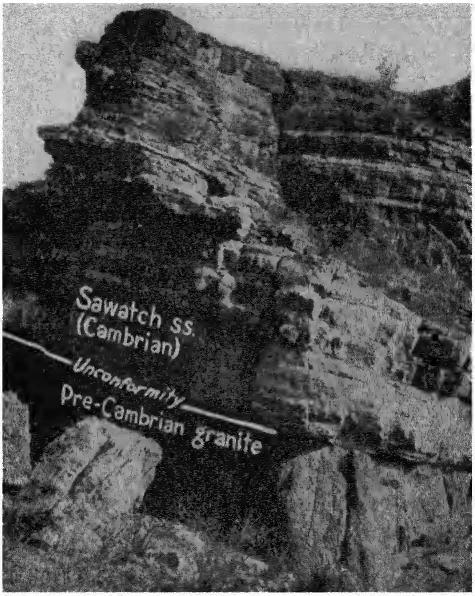


Fig. 52.—Cambrian sandstone resting unconformably on granite, near Colorado Springs, Colo. (*N. H. Darton, U. S. Geol. Survey.*)

or horizontally. Parts of the Cambrian system, many hundreds of feet thick in some regions, have almost identical lithologic characters, which means that conditions of deposition remained stable for a long time. Further, certain Cambrian formations have amazingly constant characters for hundreds of miles along the outcrop, pointing to remarkable uniformity of conditions over a large area. Study of the Cambrian rocks emphasizes also the conclusion that these deposits are practically everywhere of shallow-water origin.

Stratigraphic Divisions.—The Cambrian strata are divided into *formations*, which are the units of geologic mapping and are defined by similarity of lithologic character and fossil content. The thickness of different formations may vary between wide limits. Some are thousands

of feet thick, which is rather uncommon, others less than a hundred feet. Normally, each formation contains strata that represent uninterrupted sedimentation, or if breaks occur these are of very minor importance.

The Cambrian strata are also divided into much more comprehensive parts termed *series*. Each series contains several formations. The Waucoban (Lower Cambrian) series includes the oldest deposits of the system, and the Acadian (Middle Cambrian), St. Croixan (lower Upper Cambrian), and Ozarkian (upper Upper Cambrian) are successively younger series.

Basis for Determination of Stratigraphic Divisions.—The smaller stratigraphic units of the Cambrian, and of other systems, are determined primarily by characters of lithology, and to some extent by fossils.

The larger divisions are based upon the presence of distinct breaks or "lost intervals" in the geologic record which may be shown by physical evidence (unconformities), but also (and more importantly) by noteworthy changes in the character of the fossils. Throughout the Waucoban series, for example, certain distinctive species are common and widespread. By no means all of the species of one formation or zone within this Lower Cambrian series extend into others above or below, but changes in the make-up of the fauna are gradual. In passing from Waucoban to Acadian beds, however, there is a distinct alteration of faunal characters in which many of the older forms of life disappear and their place is taken by entirely new ones.

A relatively sudden change in the character of fossils in a succession of rock formations has a number of possible meanings. (1) Although there may be little physical record of interrupted sedimentation, it is possible that the sea withdrew for a time during which the normal slow dying-out of old kinds of life and development of new ones so modified the shallow marine faunas that, when the sea readvanced, the composition of the fauna was distinctly different. (2) Some marked geographic change may have taken place, direct connection being made between sea basins containing different forms of life. Immigration of species from one district to the other could account for the sudden appearance of new elements in the fauna, and inability of certain of the resident species to compete with the newcomers would lead to their extinction. This is apparently the chief reason for differences in the faunas of the Cambrian series. (3) Since marine invertebrates are sensitive to conditions of environment, a sudden change in environmental factors might adversely affect some species, but it could hardly be the independent cause of a sudden appearance of new types of life. All of these factors and others have doubtless operated at various times to produce differences in the faunas which became entombed as fossils in the strata. A natural subdivision of the great thickness of deposits that constitutes the geologic record is possible mainly because of these more or less sudden

changes in faunal characters. The order of succession of the fossil faunas is determined by the observed superposition of beds that contain the fossils. No single complete section of the Cambrian rocks is known, however, and accordingly it is necessary to arrange in proper order or piece together the information yielded by a number of different sections. Even this fails to provide a perfect record.

Nature of Outcrops.—The distribution of outcrops of the Cambrian rocks or of an individual Cambrian formation depends on (1) geographic distribution of the rocks, (2) their thickness, (3) structure, and generally (4) topography. In Wisconsin and Missouri where the Cambrian beds are nearly horizontal, the outcrops cover a broad area some thousands of square miles in extent, yet the thickness of these rocks is only a few hundred feet. Parts of the Appalachian region show long narrow Cambrian outcrop bands that cover a very much smaller surface area, but the exposed beds measure thousands of feet in thickness. The outcrops are narrow and linear because of the steep dips. Depending on the factors above mentioned and the extent to which erosion has cut downward into the rocks, outcrops of Cambrian may appear partly or wholly surrounding areas of pre-Cambrian rocks, or, on the other hand, more or less surrounded by pre-Cambrian; and Cambrian outcrops may appear in subparallel bands separated by older or younger rocks, or both. These characters of the outcrops of stratified formations are essentially matters of geometry and are obviously applicable to any given geologic system or smaller stratigraphic unit.

CAMBRIAN FORMATIONS OF NORTH AMERICA

Distribution.—Rocks of Cambrian age are widely exposed in North America (1) in the Appalachian region, from Newfoundland to Alabama, (2) in scattered portions of the Continental Interior, and (3) in the western Cordilleran region, including especially parts of Arizona, Utah, Nevada, California, Montana, and British Columbia.

The territory over which Cambrian sediments are distributed is much greater than the area of their surface exposure, for most of the younger Paleozoic deposits and portions of the post-Paleozoic formations are underlain by Cambrian. This is evidenced by deep well borings in many places, especially where, as in the northern part of the Mississippi Valley, Cambrian sandstones are important sources of water. Probable continuity beneath districts where the Cambrian has not been reached by drilling is indicated by its presence in so many widely scattered structural uplifts and it is also suggested by similarities in lithologic and faunal characters of observed outcrops. Also the original distribution of Cambrian rocks was greater than the present by a considerable but unknown area that has been removed by erosion. Certainly many square miles of these beds have been carried away from the Adirondack region of

New York, northern Wisconsin, the Appalachians, and elsewhere. However, there is no reason to conclude that very much of the Canadian Shield, now bare of Cambrian, was ever covered by deposits of this age. The Adirondack and Wisconsin areas were probably islands or archipelagos during part of Cambrian time.

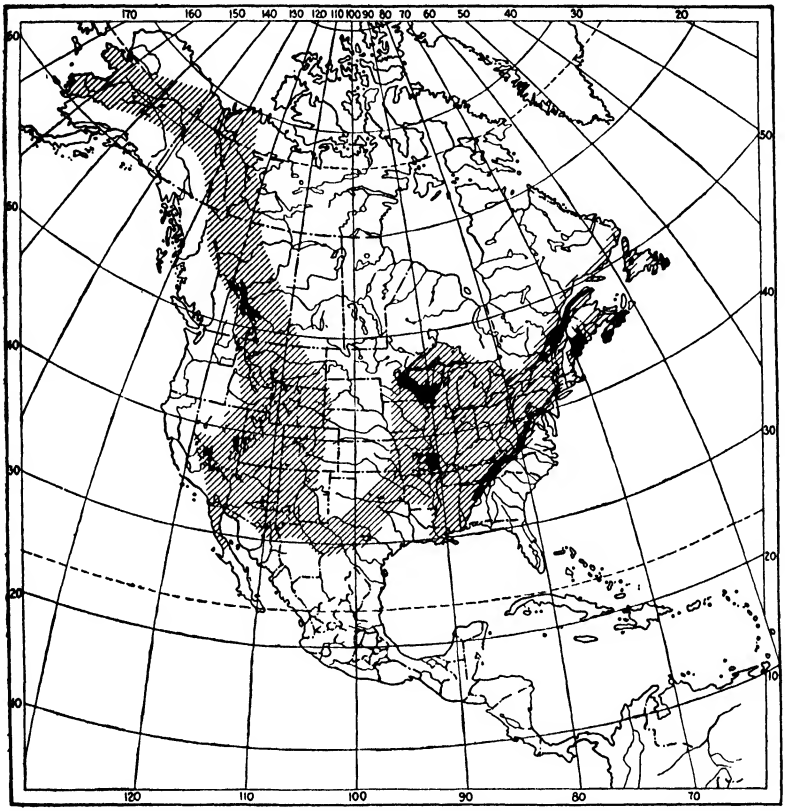


FIG. 53.—Map of North America showing (in black) the outcrop areas of the Cambrian system and (in oblique shading) the inferred area of original distribution of Cambrian formations. Throughout much of this region the Cambrian rocks are still present, more or less deeply buried under younger rocks. (*R. T. Chamberlin, in Chamberlin and Salisbury's Historical Geology, Henry Holt & Company.*)

Maritime Canada and Eastern New England

Steeply folded and faulted strata consisting mostly of greenish, reddish, and black slates and some quartzites represent the Cambrian in southeastern Newfoundland, Cape Breton Island, New Brunswick, and parts of eastern New England. These rocks are many hundreds of feet in thickness and the Lower, Middle, and Upper Cambrian are recognized. The most important feature of the Cambrian in this area is the nature of the fossils which are practically identical with northwestern European

Cambrian fossils but entirely different from those in the rest of North America. This can only mean that intermigration of fossil species between the maritime Canada-eastern New England region and Europe could occur freely in Cambrian time, and that a barrier of some sort, probably land, prevented the mingling of this Atlantic fauna with the marine shallow-water organisms of the North American interior.

The Appalachian Region

Strata of Cambrian age, more or less altered by heat and pressure, are seen in a nearly continuous belt lying in the eastern part of the Appalachian Mountains extending from northwestern Newfoundland to Alabama. The Cambrian rests unconformably on metamorphosed

FIG. 54.—Lower Cambrian quartzite on Potomac River at Harpers Ferry, Va. The strata are steeply inclined as a result of mountain-making movements in late Paleozoic time. View looking downstream eastward toward the Blue Ridge. (*Maryland Geol Survey.*)

Proterozoic or Archeozoic rocks. In eastern New York and southeastern Pennsylvania the Cambrian outcrop is marked by rounded hills, but west of the Blue Ridge in Virginia and Tennessee the rocks of this system produce some of the loftiest and most rugged topography of the entire Appalachians.

Appalachia and the Appalachian Geosycline.—The clastic character of the Early Cambrian formations throughout the Appalachian region is a distinctive feature of initial Paleozoic deposition, indicating that the near-by land from which the sediments were derived had considerable relief and was eroded rapidly. A general increase in coarseness and thickness of sand and conglomerate from west to east leads to the conclusion that the chief source of these sediments lay to the east of the area of deposition. Similar evidence is seen in various later Paleozoic deposits.

Evidently, therefore, a somewhat continuous land area extended along the eastern border of the continent during the Paleozoic era, and at times parts of the land were strongly elevated. This borderland, generally separated from the main part of North America by a recurring seaway, has been termed *Appalachia.* The elongate gulf or strait west of Appalachia, which at times was broadened by advance of the waters over the Continental Interior, was never very deep if we may judge from the frequent temporary marine withdrawals and the common presence of ripple marks, cross-bedding, and other indications of shallow water in the formations laid down here. But the fact that the sea tended to advance first and stay longest in this belt between Appalachia and the Continental Interior and the accumulation here of maximum thicknesses

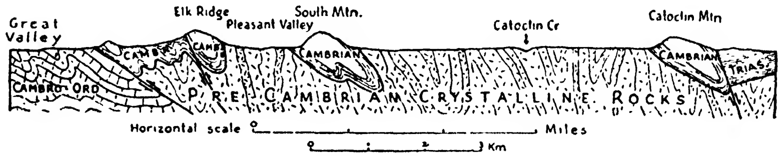


FIG. 55.—Geologic section in southeastern Pennsylvania showing relations of Cambrian formations to older and younger rocks. (*From International Geol. Cong. Guidebook 7, after Arthur Keith, U. S. Geol. Survey.*)

of sediment show that this was a tract tending progressively to sink. Accordingly, this belt is designated as the *Appalachian trough* or *geosyncline.* In contrast to the periodically uplifted or positive crustal zone of Appalachia, the Appalachian geosyncline is a persistently downwarped or negative area (see Fig. 7).

The northern Appalachians have been so intensely folded and faulted in post-Cambrian time that it is difficult to determine the complete character or thickness of the Cambrian rocks. Only the Lower Cambrian, consisting of slaty and quartzitic rocks, is present in the mountain belt of eastern New York and western New England, although Upper Cambrian strata occur a short distance to the west.

The central Appalachians, from eastern Pennsylvania to southwestern Virginia, contain a thick Cambrian section that is well exposed in many places. The Lower Cambrian is 5,000 to 9,000 feet thick, with conglomeratic, sandy, and shaly beds at the base (2,300 to 5,100 feet), overlain by massive dolomite (1,000 to 2,500 feet), and reddish sandy shale (1,000 to 1,500 feet); the Middle and lower Upper Cambrian consists of about 3,000 feet of shaly limestone; and the upper Upper Cambrian (Ozarkian) is made up of sandy and cherty dolomite about 2,000 feet thick (Fig. 56). The succession and thickness of the major lithologic divisions are about the same in Pennsylvania, Maryland, and Virginia. The hard quartzitic beds in the lower part of the Cambrian make prominent mountain ridges, while the calcareous and shaly beds tend to form valleys, except in the case of certain cherty and sandy limestones.

The southern Appalachians contain the greatest thickness of Cambrian rocks in the eastern United States, for the North Carolina-Tennessee

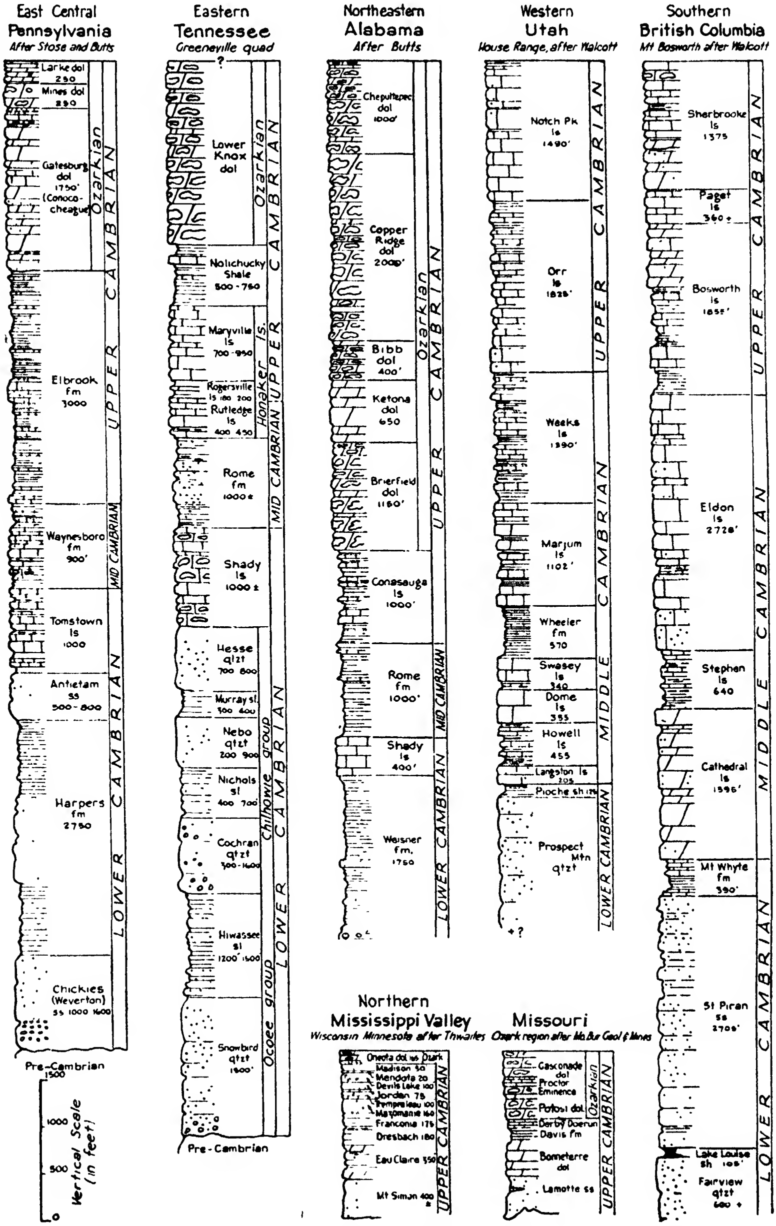


FIG. 56.—Typical sections of the Cambrian system in selected regions.

district shows 10,000 to nearly 18,000 feet of beds belonging to this system. The Lower Cambrian is most prominent, consisting mainly

of very hard, massive quartzites that make some of the most rugged topography of the Appalachian Mountains. The average thickness of the Lower Cambrian series in this region is about 10,000 feet. The grains of the quartzite are mostly rather coarse and there is much conglomerate. Dark slaty formations are interbedded with the quartzite. The enormous quantity of this rock waste, its increasing coarseness and thickness in an eastward direction, and other characters point to the former existence of a mountainous highland east of the belt now occupied by the Lower Cambrian sediments. It is estimated that this long-vanished mountain chain extended at least 200 miles from southwest to northeast and that in height and grandeur it was comparable to the present-day Alps. The presence of Lower Cambrian (Waucoban) marine fossils and thick limestone near the top of the great sand and conglomerate series shows (1) that the time when the mountains existed in this region was at least earlier than late Early Cambrian, and (2) that before the early middle part of Cambrian time erosion had reduced the mountains to lowlands. The mountains that are thus evidenced by the products of their obliteration have been named the *Ocoee Mountains*. It is possible that the elevation of the Ocoee Mountains and the deposition of the great thickness of sediments derived from them belong to Late Proterozoic rather than Early Cambrian time.

Middle Cambrian limestone beds (Rutledge, lower Conasauga) are recognized in the southern Appalachian area but their thickness does not exceed 500 feet.

An unusually complete Upper Cambrian section occurs in Alabama. The lower Upper Cambrian (St. Croixan) is here represented by thin-bedded and shaly limestone about 1,600 feet in maximum thickness. Well-preserved fossils are abundant in these beds locally. The upper Upper Cambrian (Ozarkian) rests unconformably on underlying beds and in places is found directly on Lower Cambrian. The total thickness of the Ozarkian ranges up to 4,500 feet.[1] It consists almost entirely of massive dolomite beds, part of which contains much silica in the form of chert and finely disseminated particles. This great thickness of calcareous sediment evidently represents a long time of deposition.

The Continental Interior

The Cambrian deposits of the Continental Interior, that is, of areas between the Appalachian trough and the similar belt of thick sediments in the west known as the Cordilleran trough, are generally distinguished by an absence of beds older than Upper Cambrian, by a total thickness that is measured in hundreds rather than thousands of feet, and by a relative

[1] Charles Butts, of the U. S. Geological Survey, classes the Chepultepec dolomite (1,100 feet) as upper Ozarkian rather than Lower Ordovician. If this formation is included in the Ozarkian, the total thickness of this series in Alabama is 5,600 feet.

importance of sandy sediments. Everywhere there is a profound unconformity at the base of the Cambrian, the underlying crystalline rocks having been worn down in most places to a nearly featureless plain. Basal conglomerates occur in many places. The lack of earlier Cambrian in this interior region indicates that the land remained above sea level until the latter part of the period, when advancing waters gradually flooded a very large part of the continent. The presence of the sea is shown not only by widespread uniformity of lithologic characters and even stratification, but by abundant remains of marine organisms in many of the beds. The gradual nature of the sea transgression is marked in some places by the occurrence of progressively younger deposits resting directly on pre-Cambrian rocks in the direction of marine invasion.

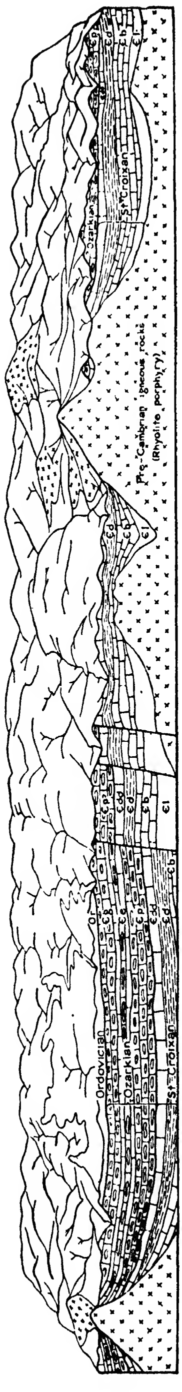


FIG. 57.—Section of Upper Cambrian and associated rocks in part of the central Ozark region. Note especially the structural and stratigraphic relations of the Cambrian strata to the rough topography of the pre-Cambrian rocks. (*Modified from C. L. Dake, Missouri Bur. Geol. and Mines.*)

Adirondack Region.—In the Adirondack region of northeastern New York, Upper Cambrian sandstone and dolomites are exposed on the north, east, and part of the south sides of the mountain area, showing in many places overlap of the younger beds. On the west side of the uplift, however, the Cambrian is overlapped by Ordovician rocks.

Lake Superior Region.—A large area south of Lake Superior in Minnesota, Wisconsin, and northern Michigan is occupied by the Upper Cambrian, consisting largely of sandstone (St. Croixan), in part strongly cross-bedded, but containing thick limestone and dolomite beds in the upper part (Ozarkian). The total thickness is about 1,500 feet. These beds extend under cover of younger formations far to the south. Some layers contain abundant fossils.

Ozark Region.—Cambrian beds appear at the surface in the Ozark region of south central Missouri. Feldspathic sandstone, with locally a coarse basal conglomerate, is the lowermost formation of the Cambrian section resting unconformably on crystalline rocks, the succeeding strata of the system consisting of several hundred feet of massive dolomite, dolomitic limestone,

calcareous shale, and sandstone (see Fig. 57). At the time the sea reached this region there were rounded hills standing more than 1,000 feet above valley lowlands, and the sandy and calcareous sediments first accumulated in the depressions before covering the hills. The bedding planes show a marked tendency toward parallelism with the uneven old topography, however, sloping more or less steeply on all sides from the hills toward the valleys. This appears to indicate that the sediments were spread in blankets of subuniform thickness over this rough topography. Excess deposition in the lower areas eventually must have obliterated inequalities of the sea bottom, but differential compaction of the thick and thin columns of sediments over the valleys and hills, respectively, would result in partial accordance of present structure of the stratified rocks and the buried crystalline rock topography. The lithologic nature of the sedimentary strata and the magnitude of the structure indicate that the first factor is probably much more important than the second.

The Ozark region contains the type section of the upper Upper Cambrian formations called Ozarkian. The rocks of this series consist almost entirely of gray crystalline dolomite containing much chert. The total average thickness is about 750 feet. Important unconformities occur at the base and top of the Ozarkian beds and there is at least one important break within the series. The latter, according to the view of some geologists, defines the boundary between Cambrian and Ordovician.

Oklahoma and Texas.—The oldest formations exposed in the intensely folded and faulted Ouachita Mountains of southeastern Oklahoma are dark sandy shales of Cambrian age, but the base of the Paleozoic section is not exposed. The Cambrian outcrop area is small, the rocks have been much metamorphosed, and the incompleteness of the section prevents definite conclusions concerning conditions in Cambrian time. In the Arbuckle and Wichita Mountains, farther west in southern Oklahoma, complete exposures of the Cambrian show a sequence of beds consisting of sandstone, grading upward into limestone, the total thickness amounting to more than 4,000 feet (see Fig. 62). Only Upper Cambrian (St. Croixan and Ozarkian) time is represented. Similar conditions are indicated in the Llano region of central Texas, and near El Paso, in westernmost Texas. A remarkable persistence of lithologic and paleontologic characters is shown by the occurrence of almost identical types of rocks and fossils in the Cambrian formations of regions as far distant from one another as Missouri and central Texas. Each of these areas, however, contains beds that are not found in the other.

Black Hills.—The Black Hills in western South Dakota are girdled by outcrops of Upper Cambrian sandstone, 5 to 400 feet thick, that closely resembles the sandstone of corresponding age in Wisconsin, far to the east, and of the Bighorn Mountains in Wyoming, some 200

miles to the west. The pre-Cambrian topography in this region was nearly featureless, for there are no large local irregularities in the thickness of the sandstone, but rather a gradual thinning from north to south.

Colorado and Wyoming.—The upturned sedimentary formations that border the crystalline core of the Rockies in Colorado and Wyoming, as seen in numerous exposures, include sandstone at the base overlain by magnesian limestone, the total thickness being 200 to 400 feet. These beds correspond in general character to the Upper Cambrian deposits of the plains region to the east and like them contain no fossils older than Upper Cambrian. The records here, therefore, prove that the sea did

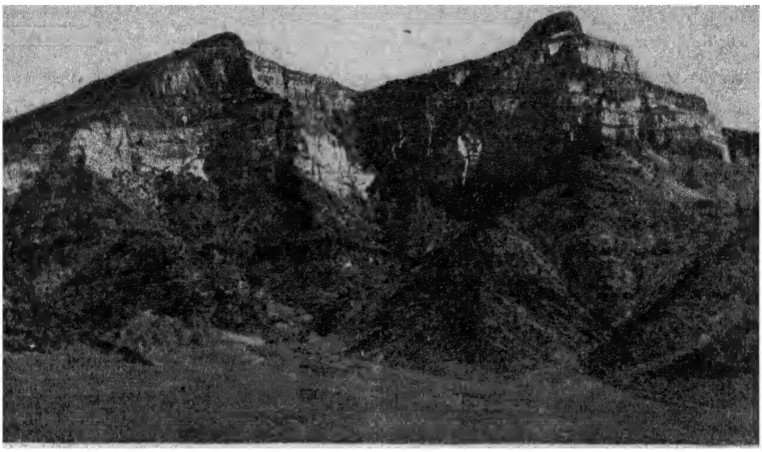


FIG. 58.—Middle and Upper Cambrian formations in the House Rock Range of western Utah. The thickness of the entire Cambrian system here exceeds 8,900 feet (see Fig. 56). (*C. D. Walcott, U. S. Geol. Survey.*)

not cover this region until relatively late in the period, and the evenness of the contact at the base of the Cambrian sandstone (see Fig. 23) shows the featureless nature of the surface that had been produced by earlier erosion.

The Cordilleran Region

Eastern California, Nevada, western Utah, and various places northward into the Canadian Rockies contain very thick deposits of Cambrian age. This country is known as the Cordilleran region. The character and fossil content of the Cambrian rocks in the Cordilleran belt have been made known mainly by the studies of the late Dr. Charles D. Walcott, who for many years was director of the United States Geological Survey and later secretary of the Smithsonian Institution.

As in the Appalachian district, the Lower Cambrian of the Cordilleran region is very thick (about 7,000 feet) and consists predominantly of sand in the form of sandstone and quartzite. The sand is composed

almost entirely of well-rounded quartz grains, representing the well-sorted, most resistant part of the rock waste derived by erosion of an adjacent land. The chief source of these sediments appears to have been on the west side of the area of deposition, for the thickness and coarseness of the sand increase from east to west. The inferred land mass has been named *Cascadia* and the belt in which the great thickness of Cambrian sediments accumulated is designated the *Cordilleran trough* or *geosyncline.*

The Middle and Upper divisions of the Cambrian in the Cordilleran trough consist mainly of calcareous sediments, thin and massively bedded, sandy and shaly limestone, and dolomite (see Fig. 56); their thickness in places is 8,500 feet. Marine invertebrate fossils are abundant in many of the formations. The rate of deposition of calcareous material on the sea floor is not rapid, and accordingly the time represented by this great section of limestone and dolomite must be very long. The Middle Cambrian of British Columbia contains 4,000 to 6,000 feet of unfossiliferous limestone, and the Upper Cambrian has ripple-marked beds with raindrop impressions and large salt cubes which indicate very shallow water and temporary exposure to the atmosphere. The Cambrian beds of the Canadian Rockies are very little disturbed in many places, and magnificent sections of the nearly flat-lying strata appear in mountain sides (Fig. 50).

The Cambrian of the southern part of the Cordilleran geosyncline is comparatively thin. In the well-exposed section of the Grand Canyon, where, as we have observed, there is sandstone at the base resting on a relatively even surface of older rocks, shaly sand and sandy shale, and at the top limestone, only the Middle Cambrian is present, its thickness amounting to approximately 1,000 feet.

CAMBRIAN FORMATIONS OF OTHER CONTINENTS

In the region where the Cambrian rocks were named—Wales—and in adjacent parts of the British Isles, the total thickness of deposits of this age is reported to exceed 12,000 feet. The strata consist largely of sandstone and shale and they have been considerably folded and faulted. The Cambrian is represented also on the continent of Europe in Sweden, northern Russia, France, Czechoslovakia, Sardinia, and Spain, some of the beds in central Europe being well-known on account of their abundant well-preserved fossils.

The Cambrian seas invaded Asia. Thick accumulations of sediment are found in China (maximum about 20,000 feet), India, and elsewhere. Upper Cambrian rocks occur in Australia and in South America.

PHYSICAL HISTORY OF THE CAMBRIAN PERIOD

The history of the North American continent during Cambrian time, including an account of general geographic and physical conditions and a record of important events, is constructed from study of the Cambrian formations. Conclusions are limited by the extent to which outcrops

furnish data and by the thoroughness of observation and accuracy of interpretation that have been given to study of these outcrops.

Waucoban Epoch.—The Waucoban (Early Cambrian) epoch may be considered to have begun with the deposition of the oldest determinable Cambrian sediments. Preceding this there had been the very long time of erosion that is marked by the sub-Cambrian unconformity. The continents were then about as large as now or perhaps larger, and the seas were restricted almost wholly to the oceanic basins. The seas of earliest Cambrian time began to advance on North America but at first they covered only a small part of the continent in the Appalachian and Cordilleran troughs. Elsewhere the land surface continued to be exposed to the atmosphere and to agencies of erosion. Later—for the most part very much later in the Cambrian period—parts of the land between the geosynclinal troughs were submerged and covered by sediments. It is evident that the unconformity in the latter region represents a much longer time than that beneath the oldest Cambrian in the geosynclines, and that the later part of the time of erosion belongs to the Cambrian. Time is continuous, and in the places where Middle or Upper Cambrian rocks rest on the pre-Cambrian it is not possible to determine how much erosion occurred in Proterozoic and how much in Cambrian time.

During much of the Early Cambrian epoch, including especially the first part, the borderlands of Cascadia and Appalachia were relatively high land. Judged by the volume and coarseness of the products of erosion of western Appalachia, this was a lofty mountain belt which has been named the Ocoee Mountains. The occurrence of the oldest known Cambrian in the western part of the Cordilleran geosyncline (vicinity of Death Valley in eastern California and southwestern Nevada) and the presence of progressively younger beds at the base of the Cambrian going eastward show also that the Cambrian sea first occupied the western part of the trough and then gradually transgressed eastward. The Lower Cambrian sediments generally are characterized by the large proportion of sand, which now occurs in the form of quartzite. The distinctive characters of the Appalachian and Cordilleran geosynclines, which consist of downward yielding belts filled with great quantities of sediments, were well defined in Early Cambrian time. Indeed, there is evidence that these features were in existence during part, at least, of the Proterozoic era.

As time elapsed, the higher portions of the borderlands were gradually worn down until, like the Continental Interior and probably most of the Canadian Shield region, they stood little above sea level. Evidence of this is found in the growing fineness and finally the virtual absence of land-derived detritus, for the upper part of the Waucoban deposits, in both the west and the east, consist of shale and limestone. In Pennsylvania

the limestone, mostly a dolomite, attains a thickness of more than 2,500 feet, and elsewhere in the Appalachian region this deposit of clear waters is commonly more than 1,000 feet thick.

The seas that invaded the eastern and western geosynclines were inhabited by many kinds of shallow-water organisms, and the faunas are so nearly identical that one cannot doubt the existence of a connection between the seas in which species could intermigrate freely. This connection is believed to have been in the far north (Arctic). There are indications also of some mingling of this northern fauna with that of the Pacific Province which is most typically developed in eastern Asia. A contemporaneous but entirely distinct marine fauna is found in easternmost Canada and New England and in part of Europe. It represents the Atlantic Province.

The close of the Early Cambrian epoch is marked by disappearance, above a certain point in the rock strata, of organisms that up to this time had been fairly common and widespread, and by introduction in rocks of later age of various new kinds of animals which persisted for a long time and which likewise became very widely distributed.

Acadian Epoch.—As in the early part of the Cambrian period, the seas which advanced over part of North America in the Acadian (Medial Cambrian) epoch appear to have been restricted to the geosynclines. Rocks of this age attain a thickness of more than 6,000 feet in the Cordilleran region. They consist mainly of thin-bedded sandy and shaly limestone, some parts of which contain abundant fossils. The nature of the sediments shows that the waters were clear and that adjacent lands were very low. Weathering processes must have continued on these lands, but the streams were evidently too sluggish to carry other than fine sediments into the sea. Whether or not there was any vegetation on these ancient lands is entirely unknown, but if there was it must have been of a very low order. The thickness of calcareous sediments, which presumably accumulate slowly, indicates the great length of time which is included in this epoch.

In the Appalachian geosyncline, several hundred feet of thin-bedded, siliceous limestone occurs above reddish sandstone and shale of the upper Lower Cambrian. Fossils are not abundant, but those which are found correspond most closely to forms from the western Middle Cambrian.

Middle Cambrian deposits which are found in eastern Newfoundland, New Brunswick, Nova Scotia, and eastern New England are of special interest because they lack the distinctive assemblage of fossils that occurs in other parts of North America but, on the other hand, contain a fauna practically identical with that of certain European localities. Evidently there were no free means of communication between the eastern Canada-New England region and western parts of the continent. Also, since invertebrates of the type represented by the Cambrian fossils could not

have crossed abyssal ocean depths, and since identity of faunal characters cannot reasonably be assumed to have arisen independently and simultaneously in distant isolated regions, we must conclude that a shallow-water means of migration existed between the east side of Appalachia and the Old World. The location of this shallow-water pathway is not known, but there is evidence that throughout most of Paleozoic time there was a land mass (*Atlantis*) extending across what is now part of the North Atlantic, and intermigration of marine organisms doubtless followed its borders. The nature and distribution of fossil faunas, as well as the character of the Cambrian sediments, thus support the conclusion that the geography of Early Paleozoic time was very unlike that of the present. Most of the deposits containing faunas of European affinities, laid down on the eastern shores of Appalachia and in parts of the Atlantic realm that are now occupied by deep water, are inaccessible and some of them have been destroyed by erosion.

St. Croixan Epoch.—The outstanding event of the St. Croixan (early Late Cambrian) epoch is the gradual inundation of the interior of the continent until most of the country between the two geosynclines and south of the Canadian Shield was covered by a wide shallow sea. The deposits that were formed in this interior region rest directly on pre-Cambrian crystalline rocks. The conclusion that this great transgression of the sea took place at a time that is later than the Early and Medial Cambrian epochs is indicated by equivalence of fossils in the Late Cambrian sediments with those in upper parts of the Cambrian in the geosynclinal areas. Everywhere the lower part of the Cambrian deposits of the interior—and in places all of them—consists of sandstone. Locally there is a basal conglomerate made up of fragments of hard pre-Cambrian rocks, broken and shifted about by waves of the advancing Cambrian sea. Very extensive cross-bedding in some of the sandstones indicates shallow water and strong currents.

In the Cordilleran trough, deposits representing the early Late Cambrian epoch consist mainly of limestone, and in places they have a thickness of more than 3,500 feet. These rocks are conformable on the Middle Cambrian. Though there is a difference in the fossils of the two divisions, there is no physical evidence of an interruption of sedimentation. The St. Croixan sediments of the Appalachian trough consist mainly of limestone and some shale. The thickness is mostly less than 1,000 feet, and in places rocks of this age are missing. Absence of these sediments may mean either that no deposits were formed in these places in the St. Croixan epoch or that erosion removed them before the next younger formations were laid down.

Ozarkian Epoch.—Time included in the Ozarkian epoch is here regarded as comprising the latest part of the Cambrian period. The rocks consist almost entirely of dolomitic and mostly very siliceous, cherty

limestones. They are found in the western and eastern troughs and in the Continental Interior. That the Ozarkian epoch represents a distinct chapter in the historical record is indicated by general recognition of unconformities above and below the formations of this age, and also by distinguishing characters of the fossil life. The time represented by the Ozarkian epoch is long, as shown by the fact that in places more than 5,000 feet of calcareous rocks were formed. The uniformly calcareous and magnesian character of the Ozarkian strata denotes clear seas bordered by low featureless lands. Lime-depositing seaweeds (algae) were an abundant and characteristic feature of these clear, shallow seas.

Close of the Cambrian.—Throughout most of North America and in other continents the strata deposited in Cambrian time were not disturbed by folding or faulting prior to the laying down of beds that are regarded as Ordovician. Therefore, the younger strata are mostly parallel to and apparently conformable upon the Cambrian; indeed, where fossils are scanty, the division between the systems may be difficult to determine. Nevertheless, the abrupt, well-marked change in the nature of the fossils that are found in the strata next above those classed as Cambrian supports the conclusion that the seas were, for a time, almost entirely withdrawn from the continent. The interruption of sedimentation and break in the continuity of the life record marks the close of the Cambrian period.

In western New England and part of eastern Canada the former sea bottom of Cambrian time appears to have been sharply elevated, with possibly some folding and faulting. The lower part of the Ordovician system in this region includes conglomerates with cobbles and boulders that contain Cambrian fossils. The rock fragments of these conglomerates are mostly angular; some of them are very large, up to one or more tons in weight; and locally there are masses up to 150 feet in length. Conglomerates with contained rock masses of such huge size are indeed puzzling. They have been interpreted (Schuchert) as in part the result of rock slides from sea cliffs undercut by the early Ordovician sea; also (Collie, Bailey, Field) as submarine landslips accompanying earthquakes due to movement along a prominent fault line which is present in this region. At all events, there is evidence of crustal instability involving disturbance of the Cambrian rocks at about this time. Schuchert has designated this movement as the *Green Mountains disturbance.*

Climate.—Southern Australia contains outcrops of glacial tillite hundreds of feet thick and traceable along the outcrop for nearly 500 miles. The tillites occur below fossiliferous Lower Cambrian strata. Similar tillites just below Lower Cambrian rocks occur in northern Norway, and they are found unconformably beneath Middle Cambrian in central China. Glacial deposits containing striated bowlders have been found also at several places near Salt Lake City, Utah, the deposits

occurring beneath Cambrian marine strata (Blackwelder, 1932). These glacial deposits have been interpreted as belonging in the Lower Cambrian, but it is probable, on the other hand, that they belong to the time of land elevation that closed the Proterozoic and preceded earliest Cambrian sedimentation. In any case there is widely scattered evidence of cold climate near the beginning of the Cambrian period.

Barrell interprets the environment under which the coarse Lower Cambrian sediments of the Appalachian region were deposited as cool and moderately dry, which is indicated by dominance of mechanical over chemical weathering with little oxidation, by presence of abundant fresh feldspars and lack of much carbon in these sediments. Later, the widespread limestones, with abundant and fairly uniform kinds of organisms, and especially the formation of great sponge reefs, as in Australia and even Antarctica, point to warmer and fairly equable conditions. Some of the Upper Cambrian formations appear to have been deposited under warm moist conditions on land, which favored thorough chemical disintegration. Inferences concerning climatic conditions at this ancient period of earth history are rather insecure, however.

Duration of Cambrian Time.—The length of the Cambrian or of other geologic periods cannot be measured accurately in terms of years. An estimate of the rate of accumulation of the various sediments multiplied by the observed thickness of the Cambrian beds gives an approximate value for the duration of time represented in the deposition of these materials, but to this must be added an indeterminate time to cover the lost intervals marked by unconformities when deposition was interrupted. Such an estimate based on study of Cambrian deposition can hardly be less than 2 million years. Determination of geologic time by the rate of radioactive disintegration suggests a figure for Cambrian time amounting to about 105 million years, and this is probably nearer the actual duration of the period.

SUMMARY

The Cambrian system comprises the oldest strata that in many places contain fairly abundant fossilized organic remains. They are separated from rocks below by a great unconformity and from rocks above by a lesser unconformity. Conditions of sedimentation varied regionally during each part of the period and changed with lapse of time in each region. The deposits are divided into formations defined by lithologic and faunal similarities, and into larger parts called series that are separated mainly on the basis of differences in fossils but in part on physical evidence of interruption of sedimentation.

The Cambrian formations are thickest and the geologic record of the period is most complete in the Appalachian and Cordilleran troughs. Deposits of Early and Medial Cambrian time are almost restricted to

these geosynclinal belts. There is evidence that the thick, coarse sediments of Early Cambrian age came chiefly from lands that bordered the geosynclines on the east (Appalachia) and west (Cascadia) where, at least in the former, there appear to have been lofty mountains (Ocoee Mountains). Subsequently, deposition of fine sediments consisting of shale and limestone indicates lowering of lands adjacent to the Cambrian seas.

The character and distribution of fossils in the Cambrian formations show that the seas of this period in the geosynclinal and interior parts of North America were freely connected. There were invasions from the north that were partly joined with the Pacific region. Southeastern Newfoundland, Nova Scotia, New Brunswick, and eastern New England contain Cambrian deposits with an Atlantic fauna that is like that of European localities and entirely distinct from other North American faunas. A land barrier separated these faunas.

The chief event of later Cambrian time was the extensive inundation of the interior part of the continent and the corresponding wide deposition of sandstone, shale, and dolomitic limestone in this region, as well as in the geosynclines. There appear to have been local disturbances of the earth crust in western New England and eastern Canada near the close of the period (Green Mountains disturbance).

CHAPTER XII

FORMATIONS AND PHYSICAL HISTORY OF ORDOVICIAN TIME

As commonly defined, the Ordovician period comprises the second division or chapter in the historical record of the Paleozoic era. The rocks composing the Ordovician system are broadly differentiated from those below and above by distinguishing features of their contained fossils, and to some extent, also, by lithologic characters. Definition of the upper and lower boundaries is based on the occurrence of widespread unconformities that denote general withdrawal of the sea from the continent and accompanying hiatuses in the record of sedimentary deposition and slowly changing marine life. As a matter of fact, interpretation of some of these features of the Ordovician record is uncertain. There has been and still exists difference of opinion as to definition of the boundaries of the system in certain places. Where evidences of physical and biologic breaks are very clear the problem is simple, but where interruption of sedimentation was slight, if present at all, there is less general agreement. Precise definition of these boundaries is not essential from our viewpoint, however, for we seek merely to determine the main facts of the geologic record and to examine the evidence concerning them.

GENERAL NATURE AND DIVISIONS OF THE ORDOVICIAN ROCKS

Lithologic Characters.—The Ordovician rocks contain almost all types and varieties of sedimentary deposits. There are conglomerates, sandstones, shales of many sorts, limestones, and dolomites. Some widely distributed beds of altered volcanic ash (bentonite) are also known. The variety and complexity of the lithologic character of the Ordovician rocks are thus comparable to those of the Cambrian and of other geologic systems. The statement, sometimes made, that the Ordovician is made up mainly of limestone deposits, is essentially true as applied to some regions, but it gives an entirely erroneous impression of the composition of the system as a whole. Some sections of Ordovician rocks thousands of feet thick contain hardly a single thin bed of limestone. Accordingly, we may recall here what was said of the Cambrian, that conditions of sedimentation varied from place to place during each part of Ordovician time; and they also changed in any one place with lapse of time.

Conglomerates are found chiefly in Lower Ordovician formations of parts of eastern Canada and are distinguished especially by the angular

character and large size of some of the constituents. In the Appalachian region there are several deposits of calcareous, shaly and massive sandstone, and in the Continental Interior there are some remarkably pure quartz sandstones, especially one widespread formation called the St. Peter sandstone. Some of the shale deposits are dark-gray to black and very thick. Others are light-gray and in places so calcareous that they grade imperceptibly into shaly limestone. Still others are sandy, and gray, yellowish, or reddish in color. Many of the limestone deposits are very pure. They show various colors, very dark to light-gray, white,

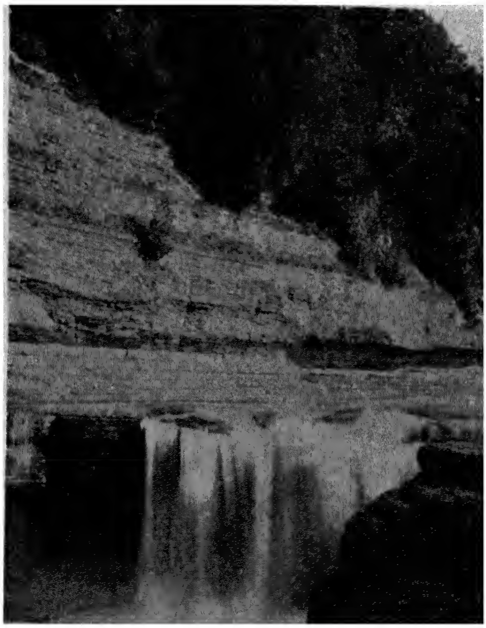


FIG. 59.—Outcrop of Middle Ordovician thin-bedded limestone (Trenton) at Trenton Falls, N. Y. (*N. H. Darton, U. S. Geol. Survey.*)

yellowish, and reddish. The texture of some is exceedingly fine-grained and dense, while that of others is coarse crystalline, almost like marble. Some of the limestones are very massive and uniform; others are very thin-bedded and highly variable. The dolomites are generally gray, weathering brownish, mostly massive, and somewhat coarse. Characteristic of some formations is an irregular, partial dolomitization which produces a mottled coloring and gives weathered rock the appearance of crumbled concrete. Some of the limestone and dolomite formations contain an abundance of chert. Many of the Ordovician formations, especially shales and limestones, are amazingly fossiliferous; indeed, few geologic systems contain a more varied or well-preserved representation of the shallow-water sea life of the time.

Divisions.—Based on lithologic character, fossils, and evidences of temporary interruptions of sedimentation, the Ordovician rocks of North America are divided into formations which for the most part bear the names of geographic localities where they were first studied and defined. In some places, subdivisions of formations have been named and described for special reasons. Some of the named formations are local, being recognized only in a certain district. Others are very widespread, and the same formation names are used wherever they are recognized. An example of the latter is the Trenton limestone (named from Trenton Falls, N. Y.). The use of a formation name at too great a distance from the type locality, however, may lead to erroneous conclusions as regards the exact equivalence of deposits in different regions. The term Trenton has thus been used unwisely or improperly in the Mid-Continent region and western United States. On the other hand, some names as applied to rocks have been extended to include deposits that are not represented at the type locality; examples are Beekmantown and Chazy. The subdivision and classification of sedimentary deposits into formations and other geologic units, definition of their vertical and geographic extent, related study of lithology and fossils, and correct nomenclature of the deposits are all embraced in the branch of geologic science called stratigraphy. In most cases the work of the stratigrapher is intensely interesting, and, of course, it plays an essential part in the delineation of geologic history. It is a task for the specially trained worker, however, since most of the problems are by no means simple, and the scope of required knowledge is a bit staggering. For instance, there are more than three thousand described species of Ordovician fossils in North America, and the number of named formations and other stratigraphic units is approximately four hundred. Fortunately, through correlation with a standard section in which there is a small number of units, the great majority of these stratigraphic names are used only in a local sense. It may be added that the so-called standard section of any geologic system is almost invariably of composite character, that is, made up of units that are not all found in a single geologic section. Thus, portions of a period that are unrepresented by deposits in one region are found to be represented in others, and the complete record may be pieced together to form a standard general section.

During Ordovician time there were three major transgressions of the sea which were separated by great or partial temporary withdrawals of the sea. These movements of the sea define major groups of formations which are termed series. These are named, in order from oldest to youngest, (1) Canadian, (2) Chazyan and Mohawkian, and (3) Cincinnatian. The differentiation of these is based on the same sort of evidence as that described for divisions of the Cambrian. The Chazyan rocks represent initial stages of the great mid-Ordovician marine transgression that

culminated in Mohawkian time, and, according to conclusions of a number of investigators, there was not an extensive withdrawal of the sea at the close of the Chazyan epoch.

ORDOVICIAN FORMATIONS OF NORTH AMERICA

Outcrops of Ordovician rocks are extensive in the eastern part of the United States and Canada, including the Great Valley district of the

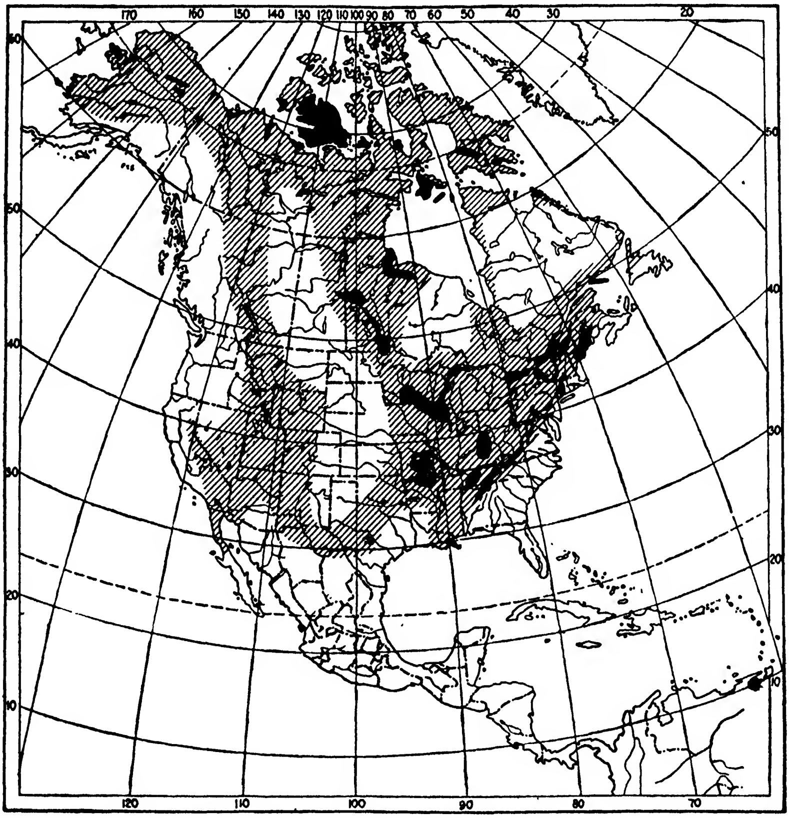


Fig. 60.—Map of North America showing (black) outcrop areas of the Ordovician system and (oblique shading) the inferred area of original distribution of Ordovician formations. (*R. T. Chamberlin, in Chamberlin and Salisbury's Historical Geology, Henry Holt & Company.*)

Appalachian Mountain region, the country around the Adirondacks in northern New York, southern Ontario, and areas centering about Cincinnati, Ohio, and Nashville, Tenn. In the central states there are large exposures in the Ozark region of Missouri and northern Arkansas, and in Wisconsin, northern Illinois, northeastern Iowa, and southeastern Minnesota. Small exposures occur in the southwest, including Oklahoma and Texas, and in several of the western states. Central Canada southwest of Hudson Bay and the Arctic Archipelago and parts of northern Alaska

are known to contain Ordovician rocks. Lower Ordovician deposits are fairly extensive in western Canada.

The Appalachian Region

Northern Appalachians.—The mountainous country north of New York City in western New England and eastern Canada, sometimes called the northern Appalachians, is important to the study of the Ordovician rocks, partly because of interesting features that are shown and partly for historical reasons. The rocks have a very complex structure, and in part they have been intensely metamorphosed. The formations are overturned in places and broken by great thrust faults. Ebenezer Emmons, a geologist of the first New York Survey, defined here, in 1837, what he called the Taconic system, named from the Taconic Mountains of eastern New York and western New England. Long and bitter controversy concerning the age and true relations of these rocks is prominent in the early annals of American geology. There is now agreement that part of these rocks is Cambrian and part Ordovician, and as the name serves no good purpose it has been dropped.

Farther north on the western shores of Lake Champlain and on the east side of the Adirondack Mountains are good exposures of Lower and Middle Ordovician limestones that, except for normal faulting, are little disturbed. The sequence of beds is definitely determinable and some of the formations contain fairly abundant fossils. These rocks were named Champlainian by the early New York geologists (1842); and because of priority over the British term Ordovician (1879), Schuchert has advocated that Champlainian be substituted for Ordovician. However, the general usage that the latter term has acquired, and the fact that only a part of the rocks generally assigned to the Ordovician system are present in the Champlain region, are reasons for using the European name. The lower part of the Ordovician section in this region consists of some 1,500 feet of massive gray limestone (Beekmantown) of Canadian age. This is followed by an erosional break and another limestone (Chazy) about 1,000 feet thick with a distinctly different assemblage of fossils. This in turn is overlaid by still younger deposits consisting of thin-bedded dark limestones (Black River-Trenton) and black bituminous shale (Canajoharie) which represent the Mohawkian epoch. The formations are cut off on the east by a great thrust fault that brings highly metamorphosed Cambrian and Ordovician rocks into contact with them.

The Atlantic Province and Logan's Line.—In eastern New York, as near Albany, and northeastward from Lake Champlain, as near Quebec, Ordovician deposits are found that differ radically from those just described. The strata (Deepkill, Normanskill) consist mostly of fine, dark-colored shale, and in places there are beds of greenish sandstone and coarse, boulder-bearing conglomerate. Moreover, the fossils are

very unlike those of the limestones, consisting almost altogether of the floating marine organisms called graptolites. Because a large number of the species of these animals occur in the Ordovician of Europe but not in the widespread limestones and shales of the same age in the interior of the American continent, the graptolite-bearing deposits are regarded as belonging to an entirely distinct province, termed the Atlantic Province.

In western New England and in eastern Canada along the St. Lawrence River, deposits of the Atlantic Province have been carried an unknown but considerable distance westward by great thrust faults, so that in places rocks of the Atlantic Province rest directly on those of the west.

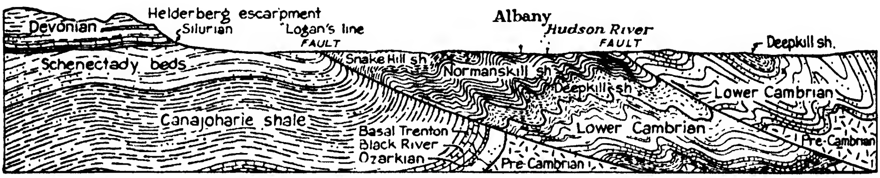


FIG. 61.—Section of Ordovician and associated rocks in the vicinity of Albany, N. Y. The Ordovician rocks east of "Logan's line" fault are graptolite-bearing black shales (Deepkill, Normanskill, Snake Hill) of the Atlantic province. The Ordovician rocks west of the fault are called Black River, Trenton, Canajoharie and Schenectady. (*Modified from R. Ruedemann, New York State Museum.*)

The line of thrust faults is generally known as *Logan's line*, after the early Canadian geologist Sir William Logan who first called attention to its significance. There yet remain important unsolved problems in the Ordovician of this region, bearing for instance on the actual geographic conditions of this time, the real meaning of the differences in sediments of the two provinces, and of the character and distribution of the fossils in them.

Central and Southern Appalachians.—From New Jersey and Pennsylvania southward into Alabama there are nearly continuous exposures of Ordovician rocks. They consist mostly of limestone and shale that form the lowlands of the Great Appalachian Valley, bordered on the east by mountainous ridges of Cambrian and pre-Cambrian rocks, and on the west by the great escarpment of the Cumberland Plateau. Locally, as in eastern Tennessee and southwestern Virginia, there are Ordovician sandstones (Tellico, Bald Eagle) that make mountains. The rocks have been highly folded, and in the southern part of the mountains they have been extensively faulted also. The outcrops of individual formations are therefore elongate narrow bands.

1. Early Ordovician (Canadian) deposits consisting of massive gray limestone (Beekmantown) extend through this region with an average thickness of about 2,000 feet, but in central Pennsylvania they attain a thickness of more than 3,000 feet. A disconformity, indicating withdrawal of the sea, is everywhere present at the top.

2. Readvances of the sea are shown by the presence of numerous formations belonging to the Chazyan series, which, however, are much thinner and less uniform from place to place than the earlier deposits. There are outcrops of shale (Athens, Sevier), sandstone (Tellico), and some limestone (Holston) in the eastern part of the mountain belt which are not present in the west, and there are formations (Ottosee) in the west which are absent in the east. There is also variation from north to south. These irregularities denote repeated minor advances and retreats of the seas.

3. The Mohawkian series is represented by widespread uniform limestones (Black River) at the base, but the upper part, which is in places very thick, consists mainly of shale (Martinsburg). The thickness of this shale is less than 5,000 feet in most places but in the north it increases to 10,000 feet, and a measured section in northeastern Pennsylvania is reported (Behre) to have a thickness of 15,745 feet. In the last-named region these rocks have been altered by folding and squeezing to a slate which is very extensively worked commercially. Upper Mohawkian limestone (upper Chickamauga) is well developed in the Alabama portion of the southern Appalachians.

4. The Cincinnatian series is partly represented in the Appalachian region by shale and sandy sediments (upper Martinsburg, Juniata) which are apparently continuous with the underlying beds. The Juniata beds, which are about 1,500 feet thick in central Pennsylvania, are distinguished by a strongly reddish color and by absence of fossils. Many of the sandy layers are cross-laminated; the shale beds are lumpy, nonfissile mud rocks. The formation is interpreted as a piedmont alluvial plains deposit that was built outward into the sea on the western border of Appalachia. The age of the formation is shown by lateral gradation into fossiliferous marine strata (Richmond) to the northwest.

Troughs and Barriers in the Appalachian Geosyncline.—Some of the Ordovician formations are widespread in the Appalachian region and fairly uniform in lithology and fossil content. These certainly represent seas that covered practically the entire geosyncline. In other cases, as noted in the preceding paragraph, a formation or group of formations is present in one region but at a little distance it grows thinner and shortly disappears. Such wedgelike deposits may have been made in subordinate troughs of the major geosyncline by seas that did not cover barriers separating the occupied depressions. As a result, there is such variation in the deposits from place to place that much confusion has resulted in geologic study. Only by thorough knowledge and careful study of the fossils in these deposits is it possible to recognize those that belong to a given stage and to determine the relations of a sequence of deposits in one place to that in another. Much of the credit for present knowledge of the complex details of Ordovician stratigraphy in the Appalachian

region is due E. O. Ulrich and Charles Butts of the United States Geological Survey.

The subordinate troughs and barriers of the Appalachian geosyncline appear to have been fairly constant features of this generally subsiding region. The troughs tended to sink more than the barriers, and it is likely that the synclinal structure of the troughs and gentle anticlinal structure of the barriers served to mark out the location of major folds and faults in the Appalachian area when it was later subjected to great compressive stresses. It is noteworthy that the elongate synclines of the present mountain belt correspond in large part to the subordinate troughs of Paleozoic time, and this is shown by the differing characters of the rock formations that are found in them.

Several formations in the Ordovician of the Appalachian region are extensive from north to south, parallel to the axis of the geosyncline, but they are restricted to its easternmost part. These formations contain fossils that are almost wholly unrelated to those of Ordovician beds farther west, in central Tennessee, Kentucky, and the Mississippi Valley. Also, the Ordovician fossils in the latter regions are almost wholly distinct from those of the eastern Appalachian belt. The seas in which the eastern formations were deposited appear to have been separated from those to the west by a barrier, probably of unsubmerged land; or, according to Ulrich, the eastern and western formations are not precisely contemporaneous, seas of different origin alternately invading the eastern and western parts of the geosyncline as a result of unequal, oscillating subsidence and tilting. At any rate, there is a very striking difference in the lithologic character and the faunas of the eastern and western belts. Many of the fossils in the eastern formations show marked similarity or identity with European fossils of the Atlantic Province. Consequently it is inferred that seas of Atlantic origin, with marine life differing somewhat from that of the interior continental seas, invaded the eastern part of the Appalachian geosyncline from time to time during the Ordovician period. At certain times and places the waters of different basins came together and consequently there was to some extent a mingling of the life in each.

It should be noted here that dissent from the inferred existence of subordinate troughs and barriers in the Appalachian geosyncline is voiced in some quarters. The axes of supposed barriers should be marked by absence of formations that occur in the adjacent troughs, for seas that made deposits in a trough are presumed not to have submerged the barrier. The general absence of linear belts that show such gaps (disconformities) in the stratigraphic succession is urged as evidence against the postulated barriers. It may be explained, however, that the position of the axes on anticlinal folds that are strongly accentuated or broken by thrust faults during mountain folding results in obliteration of most of the barrier

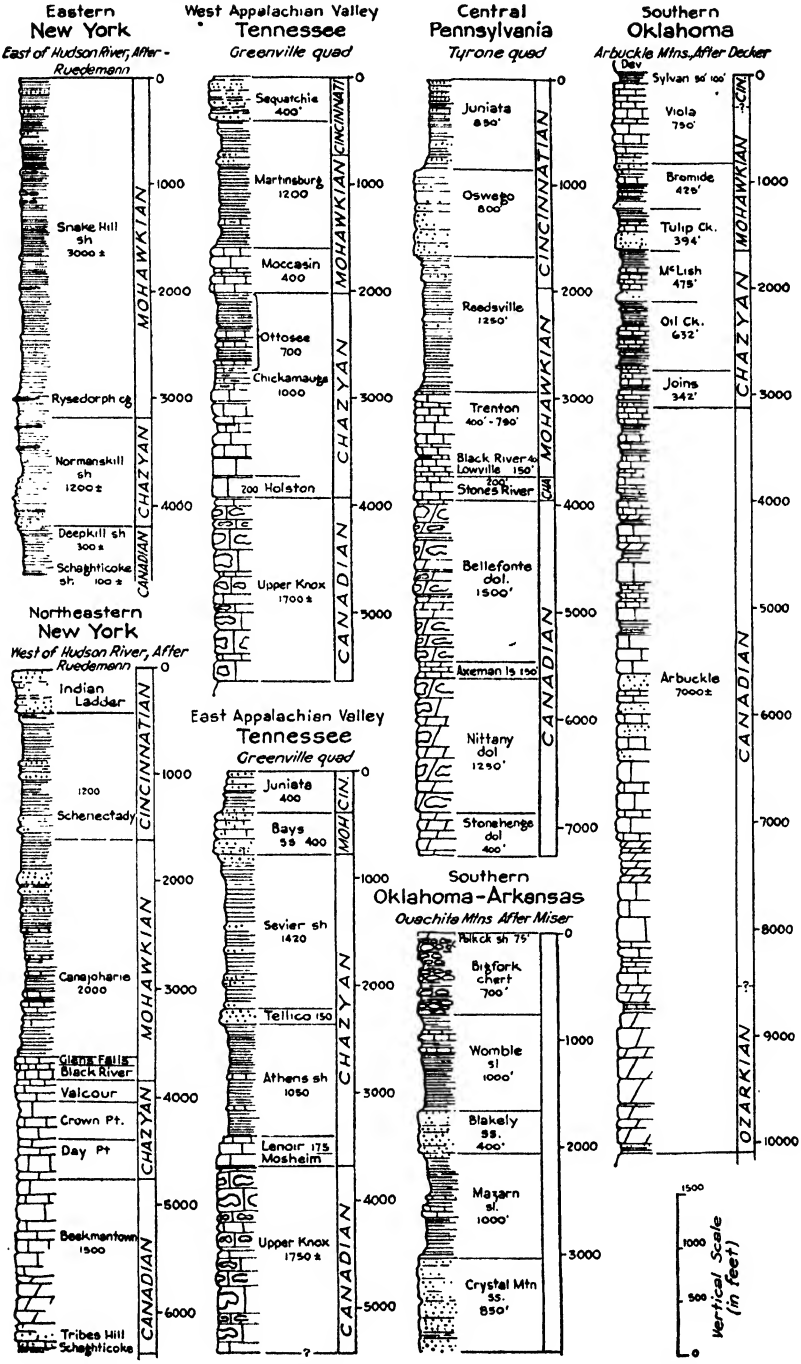


FIG. 62.—Typical sections of the Ordovician system in selected regions.

belts by erosion. Only the troughs, pressed closely together, remain. Protection from erosion is due to their synclinal structure. It is true that differences in the nature of sediment on the sea bottom are reflected in the character of invertebrate faunas, and also that one type of sedimentation (facies) may grade laterally into another. This hardly explains, however, the sharp distinctions in the lithology and faunas of the rocks in parallel troughs, and especially the remarkable persistence of distinctions that are coincident with the trough structures. It is noteworthy that the features here discussed are not restricted to a certain portion of the geosyncline but characterize it throughout its length. An east-west cross-section of Ordovician deposits in the northern Appalachians duplicates relations that are seen in a cross-section of the southern Appalachians, or of the Ouachita geosyncline (which is believed to be a continuation of the Appalachian geosyncline) in Arkansas and Oklahoma, or of the farther prolongation of the trough in southwest Texas.

The Continental Interior

Under this heading may be conveniently grouped the Ordovician formations of western New York, Ontario, the Cincinnati, Nashville and Ozark domes, and the upper Mississippi Valley. We may also include the small outcrops in the southwest and those partly covering the Canadian Shield in the north.

New York and Ontario.—Ordovician strata dip gently away from the Adirondack region and southward from the pre-Cambrian area of the Canadian Shield. Formations belonging to each of the Ordovician series are present but there are several gaps, indicating that the seas were absent at intervals and then returned to this region for a time. A gradual thinning and disappearance westward and northward of deposits belonging to the Canadian series, with overlap of younger formations, show a gradual advance of the sea in these directions during Early Ordovician time and mark the approximate limit of the invasions. The Canadian beds (Beekmantown) overlap the Cambrian in places and lie directly on pre-Cambrian rocks. The Chazyan series is partly represented in west central New York by a thin limestone (Pamelia) that marks the northeastward margin of deposits (Stones River) that are widespread to the south. A well-defined disconformity occurs below and above this formation.

Mohawkian limestone and shale deposits are extensive. In parts of this region they lie upon Canadian beds (Chazyan absent), and elsewhere they extend beyond the border of the Canadian, resting on pre-Cambrian. These relations show that the margin of the sea shifted both toward the land and away from it during Early Ordovician time, and in the Mohawkian epoch the sea advanced farther on the Canadian Shield than at any previous time in the Paleozoic era. The latter conclusion

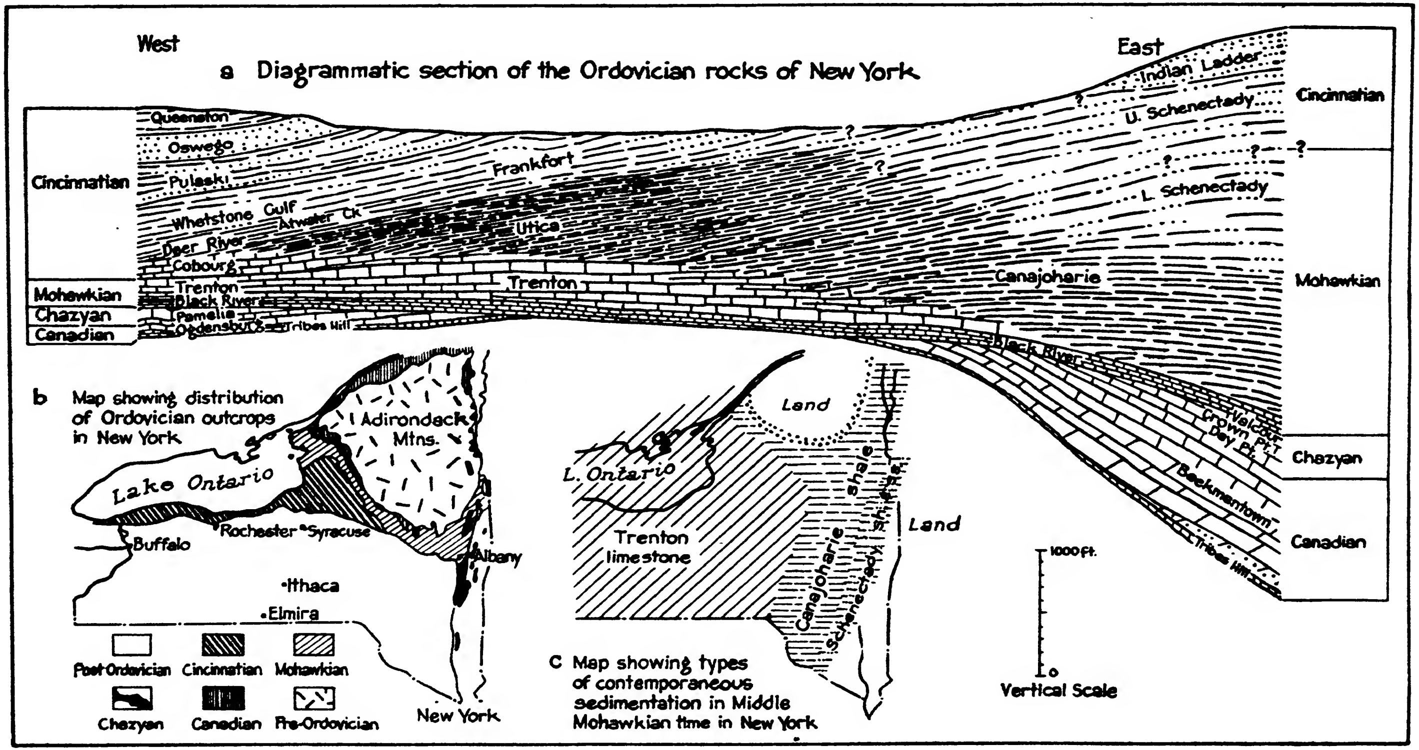


Fig. 63.—Diagrammatic section and maps showing character and distribution of Ordovician formations in New York.

is based on the assumption that the present margins of Canadian and Chazyan beds are not far from their original limits. If pre-Mohawkian erosion removed a considerable part of the earlier Ordovician rocks, it is evident that Mohawkian strata might be found unconformably on Cambrian or pre-Cambrian rocks in places where Early Ordovician deposits were once present. Fossiliferous shale with sandy beds comprises the youngest Ordovician (Cincinnatian) in the region. The Middle and Upper Ordovician section of eastern New York consists mainly of dark shales (Canajoharie, Schenectady), but that of areas farther west in the state is made up largely of limestone (Trenton) in the lower part and of sandy and shaly beds (Schenectady, Utica, Lorraine) at the top. While sand and mud were being deposited near the borders of Appalachia, limestone was being formed in the clear, but not necessarily deep, waters at a distance from the land. The mud phase begins at successively higher levels in the sections from east to west, indicating a gradual encroachment of land conditions westward (Fig. 63).

Cincinnati and Nashville Domes.—Near Cincinnati, Ordovician limestones and shales form the famous Blue Grass country of Kentucky, southeastern Indiana, and southwestern Ohio. Around Nashville the Ordovician crops out in a roughly circular lowland area which is surrounded by an upland composed of younger Paleozoic rocks. In both districts the rocks dip gently outward in all directions, making broad dome-shaped structures. In each case the oldest exposed formations are fossiliferous limestones belonging to the Chazyan series. These are overlaid by Mohawkian limestone deposits and at the top, especially in the Cincinnati region, is a series of wonderfully fossiliferous shale and shaly limestone beds that constitute the typical Cincinnatian. The profusion and perfection of preservation of the fossils in these Upper Ordovician marine deposits in the vicinity of Cincinnati, Richmond, Indiana, and other parts of this area has aroused the interest of many persons in the making of collections and in studying the remains of organisms entombed in these rocks. From the Cincinnati district have come some of the leading paleontologists of the country. The highly fossiliferous Cincinnatian deposits grade eastward and northeastward into continental sediments, the exact age of which was in doubt until the lateral transition into fossil-bearing marine beds was discovered.

A feature of some interest in the geological history of this region relates to the time of origin of the dome-shaped structures. The areas of Ordovician outcrop are surrounded by successive bands of Silurian, Devonian, Mississippian, and Pennsylvanian rocks. This arrangement indicates the possibility, or probability, that the gentle upwarping which produced the domes occurred at least some time after the time of formation of the youngest rocks that are involved in the deformation. This is no doubt true in part, but detailed study of the upper Ordovician

formations shows that the Cincinnati and Nashville areas tended to stand somewhat above the surrounding territory even in Ordovician times, for the upper parts of the domes show a thinner and less complete record of Ordovician deposits than those on the flanks. In other words, the domes show evidence of a slight but definite tendency toward upwarping that began as far back as Ordovician time, and this upward movement was recurrent and accentuated in later geologic epochs, especially at the close of Silurian time and late in the Paleozoic era.

Upper Mississippi Valley.—High, picturesque bluffs along the Mississippi River from Minneapolis to Dubuque and adjacent rugged country in Minnesota, Iowa, Illinois, and Wisconsin are built largely of Ordovician rocks. The most prominent formations are thick, massively bedded gray dolomites that weather yellowish-brown. There are two groups of these dolomites, one of Canadian and Ozarkian age (Prairie du Chien) and a higher one of Mohawkian age.

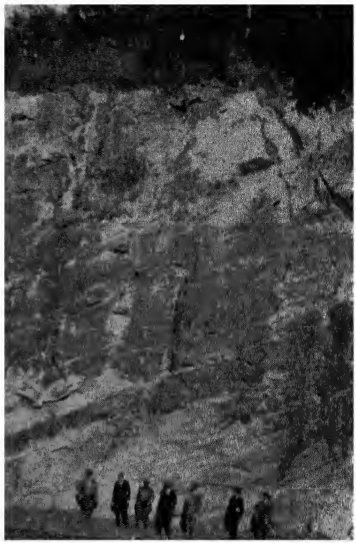


FIG. 64.—Exposure of St. Peter sandstone near La Salle, Ill. The beds here dip rather steeply westward. (*R. C. Moore.*)

Between the dolomite formations is the very persistent and interesting St. Peter sandstone. Most parts of this formation are remarkably pure, consisting only of quartz sand grains that are well rounded and in some cases frosted by abrasion and prolonged wear of one grain on another. The removal of everything but the resistant quartz grains, and the evidence of long wear of the grains has been interpreted as the result of wind work. It is certainly true that after the Early Ordovician dolomites were deposited, the seas uncovered most of the Continental Interior, for Chazyan deposits, except the St. Peter, are mostly lacking. During this time of emergence it might well be that sands derived from the Cambrian and pre-Cambrian country to the north were swept by wind and possibly by streams over territory previously occupied by the Early Ordovician seas. But the St. Peter sandstone is mostly very evenly bedded horizontally and does not show the irregularly intricate cross-bedded pattern that is characteristic of known wind-laid sandy deposits; also, in places there are poorly preserved impressions of marine shells. Thus we may conclude that, if this sand deposit was partly made and distributed by wind work, it was reworked and spread out evenly by the sea. Further evidence that the St. Peter sandstone is a marine deposit is found in the

gradation or interfingering of the sandstone into dolomitic limestones in the Ozark region.

After deposition of the upper dolomite beds, and also some limestone and thin, very fossiliferous shale, the sea withdrew for a time, as indicated by the very widespread disconformity at the base of the Cincinnatian (Richmond) deposits. These latter beds (Maquoketa) are mostly thin, that is, 100 feet or less in thickness, and they are less fossiliferous, on the whole, than in the Cincinnati district. They consist mainly of dark shale. Locally, there is some sandstone, and in places a few feet of limestone occurs.

Ozark Region and Southwest.—The sequence and general character of the Ordovician formations of the Ozark dome in Missouri and northern Arkansas are essentially similar to those just described in the upper Mississippi Valley, but there are minor variations. One feature of interest is the occurrence of limestone and one or more additional sandstones resembling the St. Peter in the southern part of the area, all belonging to the general epoch of St. Peter deposition. It appears, indeed, that sandstone of St. Peter type in Missouri and northern Arkansas is older than any of the St. Peter sandstone in the north. It was deposited before the sea advanced to the more northerly part of the Mississippi Valley. Also beds of limestone (Joachim) in Missouri are contemporaneous with St. Peter sandstone in the north. These relations show that the similar-looking sand deposits of different places are not all of exactly the same age, and that sand of the border portion of the St. Peter sea may be equivalent in age to limestone deposited at a distance from the sea margin.

In the Ozarks, as in the Cincinnati dome, there is evidence of differential upwarping of the dome that dates far back in geologic time. Upward movement was apparently inaugurated in the Cambrian period and there were recurrent elevations during Ordovician time and later.

The Ordovician formations dip gently away from the Ozark uplift and disappear beneath younger rocks. Many deep wells in Kansas, Oklahoma, and Texas have encountered Ordovician strata, parts of which have yielded huge quantities of oil. The formations come to the surface in the Arbuckle Mountains and on the flanks of the Wichita Mountains in southern Oklahoma. The thickness of Ordovician rocks in the Arbuckle Mountains is almost 10,000 feet. Above very thick Early Ordovician limestone (Arbuckle) there is about 2,000 feet of Chazyan sandstone, shale, and limestone (Simpson), the sandstone beds resembling the St. Peter in texture and appearance. Variation in the nature and distribution of the formations shows the unstable, oscillatory nature of the seas of this epoch. These are the chief oil-producing rocks in the Ordovician of the southwest. The Mohawkian and Cincinnatian epochs are represented mostly by fossiliferous limestone (Viola) that is much

thinner than the underlying parts of the Ordovician. Thick Canadian limestone occurs in the Llano region of central Texas and near El Paso in west Texas.

The Ouachita Mountains of Arkansas and Oklahoma, and Marathon area of west Texas contain slaty shale with fossils (especially graptolites) that correspond to those of the eastern Appalachian belt which belongs to the Atlantic Province. These beds are very different in lithology and fossils from the limestones and other Ordovician deposits of adjacent areas toward the Continent Interior.

An interesting observation concerning the late Cincinnatian (Fernvale) beds, which applies also to other stratigraphic units in the Continental Interior region, is the lack of any very obvious physical evidence of interruption of sedimentation below or above these deposits. The Cincinnatian beds appear perfectly parallel to strata above and below, the contacts are very even, and except for slight differences in lithology, which might have no significance at all, one would not guess that the contiguous formations differ considerably in age, representing in some cases advances of entirely different seas in different geologic periods. Here it is that the fossils furnish decisive testimony, and without them it would be impossible to determine even the main features of geologic history. It also follows from these observations that during many of the emergent stages in Paleozoic time elevation of the rocks was so slight that there was practically no erosion of previously formed deposits.

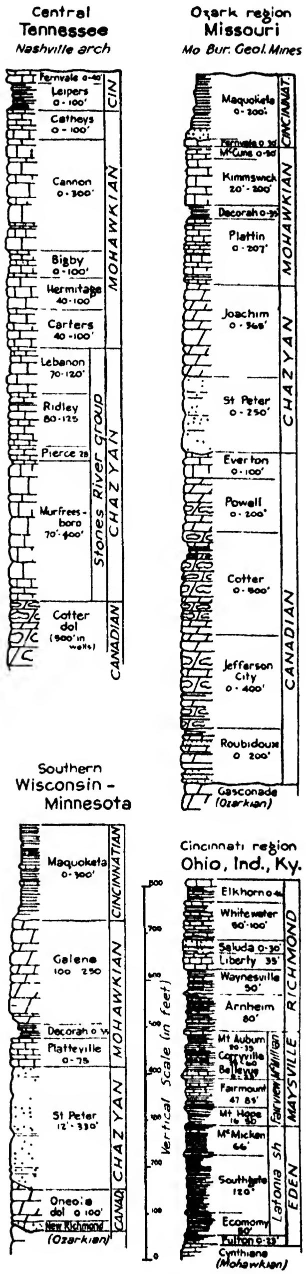


FIG. 65.—Typical sections of the Ordovician system in the Mississippi Valley region.

Central and Northern Canada.—Fairly extensive deposits of practically undisturbed Ordovician limestones occur southwest of Hudson Bay in central Canada and in the Arctic Archipelago of the far north. The deposits are only a few hundred feet thick. By means of fossils they are

identified as belonging to the Mohawkian series, and they furnish part of the evidence of the great marine transgression that occurred in Medial Ordovician time. This part of the Canadian Shield had been land since before Cambrian time, and therefore the Ordovician here rests directly on pre-Cambrian rocks.

The Cordilleran Region

Thick Ordovician deposits are found in parts of the Cordilleran geosyncline and bordering territory in the western Cordillera. In Nevada and Utah, 3,000 to 5,000 feet of Ordovician, consisting largely of limestone that belongs to the early part of the system, has been measured. The thickness of Ordovician beds is likewise some thousands of feet in the country farther north, as in the Canadian Rockies, where the beds follow the Cambrian in a parallel position with very little evidence of a break in sedimentation.

ORDOVICIAN DEPOSITS OF OTHER CONTINENTS

Wide distribution of Ordovician seas in *Europe* is attested by deposits in the northern and southern part of the continent, the former especially showing many close relationships in the fossils which they contain to the rocks in North America. Indeed, at certain times in the period there must have been a shallow-water passageway from the Baltic region of Europe, probably by way of the Arctic, to the central United States. Ordovician strata are especially known in the British Isles, Scandinavia, and central Russia. In Wales and western England the Ordovician rocks were subjected to folding and considerable erosion before deposition of the Silurian beds, the boundary between the two systems being, therefore, distinct. There was much igneous activity during Ordovician time in Great Britain, for there are many lava flows and beds of volcanic tuff. In central and southern Europe, Ordovician formations are well-known in Bohemia and parts of France, Germany, Spain, and Sardinia.

Asia contains Ordovician rocks chiefly in Siberia, China, and Burma. Ordovician rocks in eastern *Australia* and *New Zealand* yield many fossils of the floating organisms called graptolites, which are identical in kind with similar fossils in the United States. These rocks were profoundly folded and faulted at the end of Ordovician times. Ordovician rocks occur in various parts of *South America* but have not been recognized definitely in Africa.

PHYSICAL HISTORY OF ORDOVICIAN TIME

Putting together observations of the nature and distribution of the Ordovician formations in different parts of North America, and giving attention especially to information obtained from study of the abundant and varied fossils in the Ordovician rocks, we may construct an account of the chief events and changing conditions in Ordovician time. One of our chief difficulties in doing this is the very abundance of factual data and the multitudinous variation of conditions in time and place. We can set down only a few generalizations.

Canadian Epoch.—After the general emergence and local crustal movements which closed Cambrian time, the sea again transgressed a

large part of the land, not only occupying most of the Appalachian and Cordilleran troughs but expanding broadly over the Continental Interior. Locally, as in New York and Ontario, this Early Ordovician sea extended beyond areas that had been covered by Cambrian sediments, but elsewhere the deposits of this age were laid down upon the Cambrian, mostly on Upper Cambrian but locally on Middle or Lower Cambrian. Land areas were low and featureless, for the marine sediments consist almost exclusively of calcium carbonate which was carried from the lands in solution by the waters of sluggish streams. Long continuation of uniform conditions in the Canadian epoch is shown by the considerable thickness, massive bedding, and widely similar constitution of the deposits.

Chazyan Epoch.—A very widespread retreat of the sea following Canadian sedimentation is shown by an extensive disconformity at the base of the Chazyan rocks, by the physical character of the St. Peter sandstone and related sediments in the Continental Interior, and by a marked change in the character of the fossils found in the younger rocks. The Chazyan seas were mostly clear, forming limestone, but they were unstable in distribution, slowly advancing and retreating so that deposits belonging to one part of the epoch are present in one place and absent in another. Also, there is clear evidence that seas of different origin, from the north or west, or from the south or east, advanced alternately or in some cases simultaneously over parts of the continent. This is shown by the distribution of formations and the similar or dissimilar character of their fossils. Greatest complications of the historical record are seen in parts of the Appalachian district, for interwedging deposits of different seas that invaded this region during the epoch point to continuous local oscillation of the waters.

The Mississippi Valley region mostly lacks Chazyan deposits except the widespread St. Peter sandstone, the formation of which has already been discussed. The St. Peter and associated rocks are placed by some in an intermediate series between the Canadian and Chazyan. Under this classification, Chazyan sediments are altogether lacking in this region. The Chazyan is represented, however, in southern Oklahoma (Simpson beds).

Mohawkian Epoch.—The greatest marine inundation of North America in the Ordovician period occurred in Mohawkian time. That the sea covered quickly an enormous territory is shown by the remarkable geographic extent of the basal Mohawkian beds (Black River). As far as can be determined, the Mohawkian seas extended uninterruptedly from Texas to the Arctic and covered almost all of the Eastern Interior of the continent, and also the Appalachian and Cordilleran geosynclines. It does not follow that the sea of Mohawkian time was as extensive during all of the epoch as the area covered by some part of the Mohawkian series, for some of these deposits are very much older than others and the

outlines of the sea were certainly not constant. Nor is there evidence that the Mohawkian sea ever attained at one time the areal extent of the series as a whole. It is true that the marine invasion of the continent during this epoch was one of the greatest of recorded geologic history, but the sea occupied somewhat different areas in the general region of submergence in the early, medial, and later parts of the epoch.

An uplift of Appalachia in Mohawkian time began to spread a vast quantity of mud and sand into the shallow seas of the Appalachian trough, and as the thickness of sediments increased there was gradual subsidence, just as had occurred before in this region.

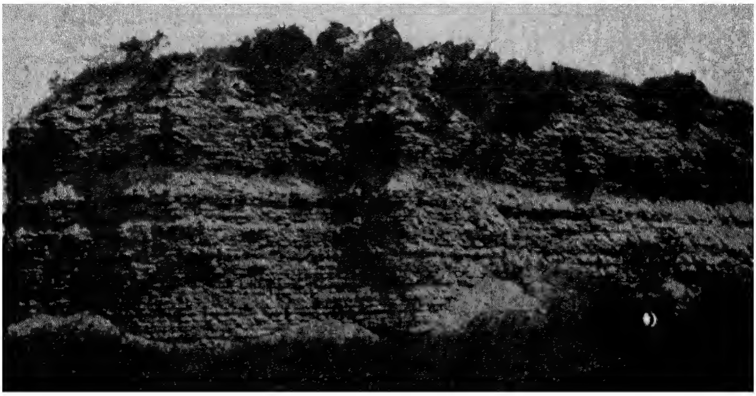


FIG. 66.—Outcrop of Cincinnatian beds (Fairmount) west of Cincinnati, Ohio. (*R. S. Bassler, U. S. National Museum.*)

Cincinnatian Epoch.—The history of earlier Cincinnatian time is recorded by deposits that are essentially restricted to the Cincinnati region and parts of the Appalachian trough and New York. Deposits of this age appear to be present locally south and southwest of the Ozarks also. The sea which covered this region shows evidences of having a southern rather than a northern origin. In the Cincinnati region the waters were moderately clear and shallow, and they literally teemed with life. In the Appalachian region, however, silt, sand, and gravel were carried by streams from Appalachia to the geosynclinal subsiding area. The increasing coarseness of the sediments implies an upward movement of the borderland which foreshadowed the greater disturbances in this district at the close of the period.

Later Cincinnatian time is represented by very widespread deposits (Richmond and equivalents) which denote a great but comparatively short-lived inundation of the continent. Many of the fossils of this age are similar to species that invaded from the north in early Mohawkian time. They appear to be the modified descendants of this Medial Ordovician Arctic fauna. It is noteworthy that late Cincinnatian strata

are found in the far northern parts of North America and that rocks of this age, carrying a very closely similar fauna, occur in the Baltic region of Europe. Many of the American and European Late Ordovician species of fossils are identical, indeed—a fact that can be explained only on the basis of a shallow-water connection between the two continents that permitted intermigration of shallow-water organisms. It appears, then, that the intercontinental connection was in the north and that the sea spread southward from the Arctic. The waters covered most of the Continental Interior region, advanced eastward to the borders of Appalachia, and spread westward into the Cordilleran trough.

New York and the Appalachian region extending southward to Alabama was apparently land in Late Ordovician time. A wide alluvial plain composed of fine sediments carried westward from Appalachia was built here. Much of the alluvial deposit (Juniata, Queenston) is reddish in color, owing to oxidation of iron in the weathered rock from which the sediments were derived or to oxidation during transportation and deposition. The formations of nonmarine origin are unfossiliferous, but on the side toward the sea they interfinger with fossiliferous marine strata. This interfingering alternation of deposits marks the fluctuations of the sea border, which periodically advanced over parts of the plain and then receded as the land was built outward.

Vulcanism.—The Middle Ordovician strata of several of the eastern states contain one or more beds of a peculiar clayey substance called *metabentonite,* formed by decomposition of a volcanic ash. The thickness of the beds ranges from a few inches to about 7 feet, but the area over which they have been found is so large that the aggregate volume is very considerable. The metabentonite beds are a valuable aid in precise correlation of the formations containing them. The reason for this lies in the exact contemporaneity of the different parts of a volcanic ash fall, and in proportion as the ash bed is widely spread the time relations of associated strata in distant exposures may be determined with definiteness.

Basaltic lava of Ordovician age has been discovered recently in eastern Pennsylvania. On the whole, however, the Ordovician period is distinguished as a time of quiet, with crustal movement and igneous activity distinctly a minor feature.

Climate.—Inferences concerning the climate of Ordovician times are based on observations of physical characteristics of the formations and on the nature and distribution of fossil life. Wide seas and low lands, such as appear to have prevailed in Ordovician time, suggest humid but probably not very rainy conditions. The most important temperature-regulating factors in the atmosphere are water vapor and suspended dust particles. Increase of atmospheric water vapor has a blanketing effect which retards earth radiation and increases the temperature, while a decrease of this constituent and the presence of much dust (as from

explosive volcanic eruptions) work in the opposite direction. Greatly expanded seas and diminished lands favor increased evaporation, while low relief of the lands tends to inhibit removal of the atmospheric moisture in the form of rain. The geographic conditions existent in Ordovician times should have produced a warm, equable climate.

Similarity of the character of marine life in the shallow seas of the continent in Ordovician times shows no zonal or other distinguishable temperature variation. The fact that warm-water-loving organisms, such as the corals, are about as common in the Ordovician of Arctic regions as in the central Mississippi Valley implies moderately warm, uniform conditions, but climatic inferences based on this kind of evidence are unreliable.

Close of the Period.—The close of Ordovician time is marked by a very general withdrawal of the sea and emergence of the land. Beneath the next younger deposits, belonging to the basal Silurian, there is almost everywhere a well-defined hiatus representing lack of deposition and locally considerable erosion of Ordovician rocks. The northern part of the Appalachian trough, in Pennsylvania and New York, was subjected to mountain-making crustal movements near the close of Ordovician time, for the Ordovician formations were folded and metamorphosed and they were greatly eroded before deposition of the Silurian in this region. Basal Silurian conglomerates here rest on the beveled edges of the older rocks and contain pebbles of slate and hard fine standstone derived from the Ordovician formations. This local mountain-making movement has been termed the *Taconic disturbance.* The great interior part of the continent was not deformed, nor could it have been elevated very much above sea level, for the older formations underwent very little erosion and the Silurian deposits are parallel to those of the Ordovician.

ECONOMIC RESOURCES

Ordovician rocks are very important to man, for in the United States alone many millions of dollars come from them annually. The total production of new wealth from Ordovician materials is probably measured in billions of dollars. The application of geologic science to the development of mineral resources belongs to economic geology, but there is a historical aspect of the subject which properly may be considered briefly here.

Petroleum and Natural Gas.—The most important of the economic products from Ordovician rocks are petroleum and natural gas. The chief regions where they have been secured are on the northern flank of the Cincinnati arch in eastern Indiana and northwestern Ohio, and in the Mid-Continent oil fields of Oklahoma and Kansas. In the Ohio-Indiana region production of oil and gas comes from the Trenton limestone of Mohawkian age, which on the average occurs about 1,000 feet below the surface in this region. Production began in 1885, and maximum development of oil in the Ohio fields was attained in 1896 with more than 23,000,000 barrels for that year. The maximum in Indiana was 11,300,000 barrels in 1904. Several of the great fields of the Mid-Continent region produce from Ordovician rocks, the greatest being the Seminole and Oklahoma City fields of Oklahoma. The Seminole district had a daily

production of 562,000 barrels in part of July, 1927, and its total yield to Jan. 1, 1932, most of it from Ordovician rocks, was 321,000,000 barrels. The Oklahoma City field is reported to have had a potential production of about 1,000,000 barrels a day.

There is abundant geologic evidence that oil and gas are derived from organic matter, probably including either or both that of plants and animals, which is deposited with the sediments. Heat and pressure in the rocks aid in changing the organic matter to oil or gas. In general, there is a movement or migration of the oil and gas through pore spaces in the rock, induced by various causes, and accumulation takes place where favorable geologic structure and porosity afford opportunity for lodgement. Sandstones commonly have a relatively high porosity, and partly for that reason the "Wilcox" sand (Simpson, Burgen) of the Ordovician in Kansas and Oklahoma is one of the main oil-bearing formations. In parts of Indiana and Ohio the Trenton limestone is dolomitic and very porous. An anticline, or other relatively upraised structure involving the porous formation, offers opportunity for the greatest accumulation of oil and gas, because these, being lighter than the salt water which commonly fills pore spaces in the deeper rocks, rise to the highest possible part of the porous rock.

The application of geology to the finding and developing of oil and gas now calls for the services of many hundreds of geologists.

Lead and zinc ore of commercial importance occur in the Middle Ordovician (Mohawkian) dolomitic rocks of southwestern Wisconsin and adjacent parts of Illinois and Iowa. The ore, consisting of the sulphides and carbonates of these metals, occurs in crevices and solution cavities, and as replacements of the limestone. Originally disseminated in overlying rocks, the metallic minerals are thought to have been dissolved by action of ground water, carried downward and deposited in the places where they now occur. Zinc ore occurs also in Lower Ordovician rocks of eastern Tennessee.

Cement Rock.—Limestones and shales of Medial Ordovician age in eastern Pennsylvania and northern New Jersey are quarried on an enormous scale for manufacture of cement. This is the leading Portland cement-producing area in the country. Much cement and lime is made from Ordovician rocks in Illinois and Missouri.

Lime phosphate, used for fertilizer, comes from Ordovician rocks of central Tennessee. The deposits have been formed by solution and removal of calcium carbonate of the phosphate-bearing formation, leaving a residual concentration of the phosphate.

Manganese ore, which supplies the material for valuable steel alloys, is concentrated in a similar way from Ordovician formations in parts of the Appalachian region and in northern Arkansas.

Building and ornamental stone of many sorts and *roofing slates* also come from Ordovician rocks.

Glass Sand.—The St. Peter sandstone in Illinois, Missouri, and elsewhere and lower Middle Ordovician sand in Oklahoma is quarried extensively for manufacture of glass. Lack of impurities makes it suitable for manufacture of plate glass and optical glass. The sand is also used for moldings in foundry work. Because of uniform roundness and size of the grains, a certain screened portion of the St. Peter sand is used as a standard in making cement blocks for tests. It is known as Ottawa sand (from Ottawa, Ill.).

SUMMARY

The Ordovician rocks are separated from preceding and succeeding deposits by widespread interruption of sedimentation. In North America, however, the beds of the older Paleozoic systems are laid regularly one on another in parallel position, except in the northern Appalachian

region where Ordovician and older rocks were folded and partly eroded before deposition of the Silurian.

The Ordovician formations are thickest in the geosynclinal troughs, where also is a maximum amount of shale and sand. Throughout most of the Continental Interior region and especially in the lower and middle parts of the geosynclinal deposits, limestone is the dominant rock. Marine invasions from different oceanic basins are identified by distinguishing features of the fossils contained in the various formations. There were many oscillations of these seas. In the Appalachian region the distribution of the shallow seas was probably controlled in part by subordinate troughs and barriers. In the interior region there is evidence of domal upwarping in the Cincinnati, Ozark, and Nashville areas.

(1) Early Ordovician (Canadian) time is characterized by widespread seas in which thick, massive limestone deposits were formed. (2) In the next epoch (Chazyan) there was a general emergence, especially of the Continental Interior, followed by submergence in which several limestone formations were made, and in the eastern part of the Appalachian trough a good deal of shale and some sandstone. The St. Peter sandstone of the Mississippi Valley region belongs to this epoch. (3) The third epoch (Mohawkian) witnessed the greatest marine invasion of the continent in Ordovician times, the sea not only covering the geosynclinal areas and the interior region but reaching northward across the Arctic Circle into Northern Europe. Parts of the deposits of this epoch, however, are local in distribution and there were numerous oscillations of the seas. Deposition of shale on a large scale occurred in the central and northern Appalachian region. There is some evidence of volcanic activity in the eastern part of the United States, although conditions were generally quiet. (4) The closing part of the Ordovician period (Cincinnatian epoch) was marked by seas in which there was a marvelous profusion of marine life.

The climate of Ordovician time appears to have been generally warm and without much contrast in different places.

Economic products of great value are found in Ordovician rocks. These include especially oil and gas, lead and zinc, lime phosphate, and glass sand.

CHAPTER XIII

FORMATIONS AND PHYSICAL HISTORY OF SILURIAN TIME

The Silurian period follows the Ordovician and may be regarded as closing the Early Paleozoic subera. If one may judge from comparative thickness of sedimentary formations, it is clear that the Silurian is a shorter division of time than the Ordovician, which serves to remind us that a geologic period has no definite or standard length. Ideally, a geologic period is defined by major pulsations of sea and land, the continent tending to be largest and most highly emergent at the beginning and close of a period, and most extensively inundated by the seas in the medial portion of a period. Life in the seas has gradually changed with lapse of time. Biologic change is apparently accelerated at times of greatest geographic change, so that faunas representing the successive times of major sea transgression differ very appreciably. Accordingly, by means of physical evidence and the nature of the fossils it should be easy to divide the rocks (and the time which they represent) into major units. These may be not at all equal in value, however. In general, the method of defining periods of geologic time in this way works out very well, but there are many deviations from the ideal cycle of marine advance and retreat in a geologic period.

Definition of the Silurian.—Following the almost complete emergence of North America at the close of Ordovician time, there is evidence of (1) a transgression of the seas in part of the central and eastern United States accompanied by extensive sedimentation of coarse land-derived waste in the Appalachian region, (2) later, a great marine inundation that covered most of the central and northern portions of the continent, followed by (3) a great restriction of the sea, with development of a large basin of strongly saline waters in the eastern Great Lakes region, and finally (4) a nearly complete withdrawal of the sea from the continent. This corresponds fairly well to the normal geologic period. The beginning of the transgression (1) marks the commencement of Silurian time, and the withdrawal of the sea (4) defines the close of the period.

An angular unconformity is found at the base of the Silurian strata in parts of the Appalachian region, especially in eastern Pennsylvania and New York. The Ordovician rocks, which were folded and to some extent metamorphosed by the Taconic disturbance, were subjected to erosion that beveled the folds and the basal Silurian beds lie on the tilted and truncated older rocks. Pebbles derived from the Ordovician formations

are seen in the Silurian layers above the plane of unconformity. Elsewhere, as in most of the central states, the attitude of the Ordovician and Silurian beds is parallel, but the boundary between the systems is indicated by well-marked differences in the lithology and faunas of the contiguous formations, by the presence locally of pebbles of Ordovician rock in the base of the next younger deposits, and by the occurrence of bottommost Silurian strata on different formations of Ordovician age in

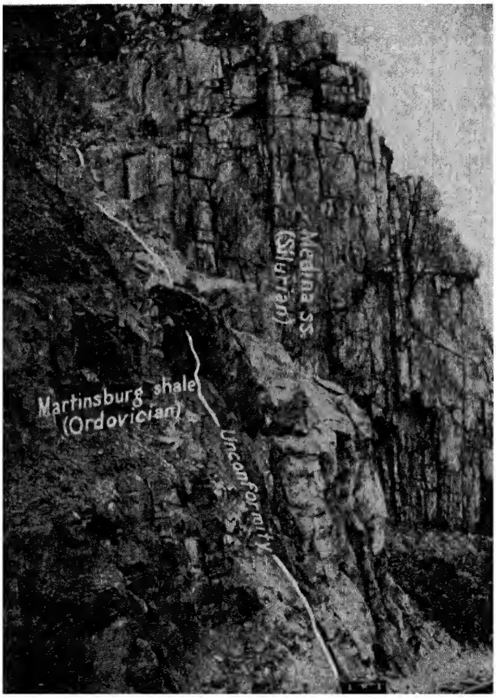


FIG. 67.—Contact of Ordovician and Silurian rocks near Port Clinton, Penn.

The dip of the beds is approximately parallel to the lettering. The Silurian beds were horizontal when deposited and they rested on the eroded edges of nearly vertical Ordovician strata that had been folded in the Taconic disturbance. Post-Silurian mountain-building has tilted the Silurian beds very steeply and has brought the Ordovician rocks back nearly to a horizontal position. (*N. H. Darton, U. S. Geol. Survey.*)

different regions. The boundary between Ordovician and Silurian rocks is thus established on both physical and biologic evidence.

A pronounced break between the Silurian and the Devonian systems is observed in most parts of North America. The upper boundary of the Silurian in these places is accordingly easy to determine. It appears, however, that in much of the Appalachian region sedimentation was almost uninterrupted from Late Silurian into Early Devonian time. The occurrence of transition beds that connect successive geologic systems is not surprising, especially in places near the margins of the continents. Incomplete withdrawal of the sea permits development of an unbroken

sequence of marine deposits in areas that remain submerged during an interval of general continental emergence. The location of the boundary between Silurian and Devonian in the Appalachian region, as defined in various geologic reports of recent years, has been based on comparison of fossils in the respective formations with those from type sections in Europe. The line has been drawn at the base of a certain limestone (Keyser) that lies conformably on Silurian beds, but it is now concluded by geologists who have studied these rocks most carefully that the Silurian-Devonian boundary really belongs at a higher horizon (base of Coeymans limestone) which is marked by a very persistent unconformity.

The close of the Silurian in Europe is marked by a profound mountain-building disturbance. Had the Silurian been defined on the basis of American deposits solely, the upper boundary would properly have been drawn to coincide with the maximum retreat of the sea, which occurred before the close of the European Silurian. Conditions on one continent may thus differ from those on another.

GENERAL CHARACTER AND DIVISIONS OF THE SILURIAN ROCKS

Lithologic Characters.—The Silurian formations consist of conglomerate, sandstone, shale, limestone, and dolomite. The beds of conglomerate and sandstone are mostly restricted to the lower part of the system in the Appalachian region. They are very prominent here, forming great mountain ridges. The shale formations are light- to dark-colored, and, especially in the east, there are large quantities of fine red sediments. Some of the shale consists mainly of clay, some is highly calcareous, and some contains much fine sand. Fossils are very abundant in some beds but lacking in others. The limestones, which are mostly magnesian, and the dolomites are widely distributed in the Continental Interior. Some of these formations are thinly and evenly bedded, others very massive and almost without bedding planes. A few of the Silurian limestones are very pure, fine- to coarse-grained, and a few are oolitic. A subordinate but very interesting type of sedimentary rock consists of iron ore, which is widespread in the lower Middle Silurian of the Appalachian region. There are also beds of gypsum and thick beds of salt in the Upper Silurian of the country about Lake Erie and in Michigan.

Divisions.—On the basis of marine oscillations and attendant distinguishing characters of the fossils in the marine deposits, the Silurian rocks of North America are divided into three series, of which the oldest is termed the Medinan, the middle the Niagaran, and the youngest the Cayugan. The Medinan formations include very fossiliferous limy shale and limestone, red and gray unfossiliferous shale, and thick massive sandstone. The Niagaran contains the chief limestone and dolomite formations of the Silurian, but there is also much shale. The iron-ore zone that has been mentioned occurs in the Niagaran, and locally there are

thick sandstone and conglomerate beds. The Cayugan contains red and gray, mostly unfossiliferous shale, limestone, dolomite, salt, and gypsum.

SILURIAN FORMATIONS OF NORTH AMERICA

Distribution.—Outcrops of Silurian rocks occur mainly in the eastern and northern parts of the continent. In New York, where these rocks were first studied carefully and where the major divisions were named, the

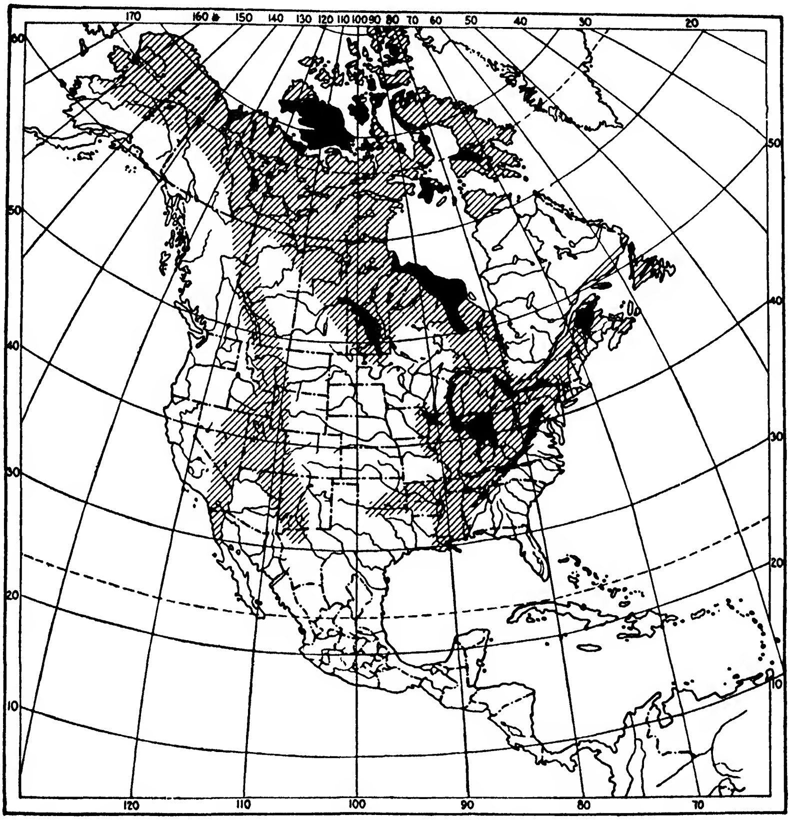


FIG. 68.—Map of North America showing outcrop areas of the Silurian system (black) and the inferred area of original distribution of Silurian rocks (oblique shading). (*R. T. Chamberlin, in Chamberlin and Salisbury's Historical Geology, Henry Holt & Company.*)

Silurian rocks occur in a band which crosses the state in an east-west direction just south of Lake Ontario. Trending northwestward, the outcrops extend across Ontario and, except for local breaks where the waters of Lakes Huron and Michigan cover them, may be traced in a continuous belt along the southern border of the northern Michigan Peninsula and eastern Wisconsin to Illinois, Indiana, and Ohio. On the north side of the Cincinnati arch the Silurian covers a large area, but

farther south and on the flanks of the Nashville uplift the outcrops are narrow. The Appalachian region, from southeastern New York to Alabama, contains outcrops of the Silurian formations, some of which, as already stated, are topographically very prominent. In addition to these areas, Silurian beds are known in Arkansas, Oklahoma, Missouri, and Iowa. They occur also in eastern Canada and Newfoundland, and southwest and north of Hudson Bay. Silurian deposits are reported in the Cascadian geosyncline.

The Type Silurian Section in New York

The sequence of Silurian deposits in western New York, because of relative completeness, simplicity of structure permitting definite deter-

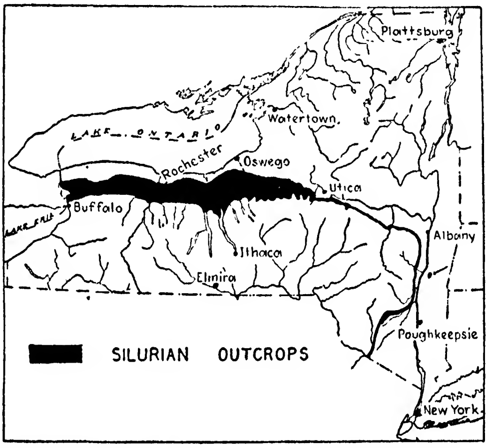


FIG. 69.—Map of New York showing outcrop area of Silurian rocks. (*Winifred Goldring, New York State Museum.*)

mination of stratigraphic succession, and occurrence of fossils, but especially because of the pioneer work of New York geologists, has come to be regarded as the type Silurian section for North America. The rocks dip gently southward, the oldest beds appearing, therefore, in the north and the youngest in the south. The section is imperfect, especially in the lower part, in that only the near-shore edges of some of the deposits are present. New York was located near the margin, rather than in a central part of the general region of Silurian sedimentation. Accordingly, some parts of the Silurian are better developed and much more fossiliferous in places outside New York.

Medinan Series.—The basal Silurian in western New York consists of sandstone and sandy shale that is well exposed in the gorge of Niagara River. A coarse white sandstone overlies Upper Ordovician red shale in this region and is succeeded by alternating gray and reddish shale and sandstone beds, some of which contain marine fossils. The total thick-

ness of the Medinan series in the Niagara River section is only 120 feet. Rocks of this age are traced westward into Ontario, where they become marine shales and limestones, but they disappear eastward before central New York is reached.

Niagaran Series.—The Middle Silurian Niagaran series consists of two main parts, the lower composed mainly of shale and limestone (Clinton) and the upper consisting of massive dolomite (Lockport). At the base of the Niagaran in western New York is a thin sandstone (Thorold), which is represented in the central part of the state by a conglomerate (Oneida) 50 to 75 feet thick. The next overlying strata consist chiefly of greenish, purplish, and bluish gray shales. There are also some thin limestones and thin beds of iron ore. The ease with which

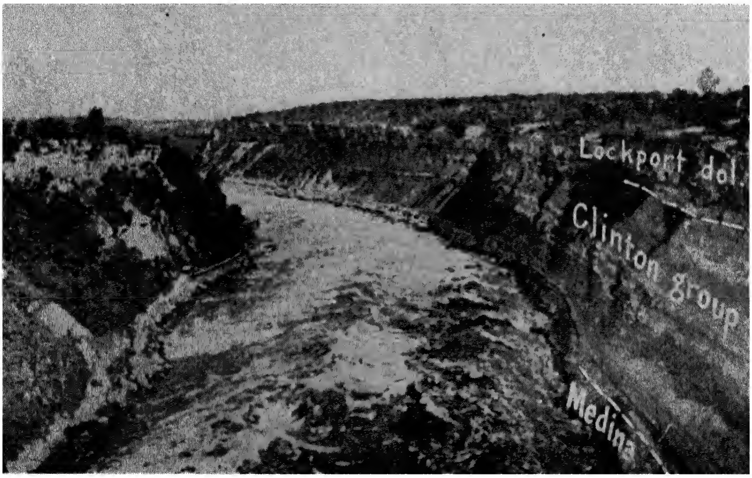


FIG. 70. Downstream view of Niagara River gorge showing Silurian formations. (*Courtesy of New York State Museum, Albany, N. Y.*)

the soft Clinton rocks are undercut by the waters of Niagara River, coupled with the strongly resistant character of the massive Lockport dolomite in this area, is primarily responsible for the existence of Niagara Falls. The upper Niagaran rocks form a prominent north-facing escarpment, which is one of the most striking topographic features in central and western New York and in Ontario.

The Middle Silurian is represented in eastern New York by very massive, resistant conglomerate and sandstone constituting part of the Shawangunk formation. This formation, which is as much as 1,500 feet thick in places, includes beds of Medina age at the base and probably of Cayugan age at the top. It rests unconformably on folded and eroded Ordovician rocks. The coarse material of this Silurian formation was evidently derived mainly from neighboring uplands of Appalachia that existed to the east of the New York region. The conglomerate forms prominent mountain ridges.

Cayugan Series.—The lower part of the Cayugan series consists of alternating red and gray shale that forms a gently rolling plain. Beneath the zône of active ground-water solution, there are numerous salt beds, ranging in thickness from a few inches to many feet, the aggregate thickness in places being 300 feet. Calcium sulphate, in the form of anhydrite and gypsum, also occurs. The upper part of the Cayugan, as seen near Buffalo and to the east, consists chiefly of dark-colored, rather thinly bedded, impure limestones which have the property, when ground and burned, of forming a cement which sets under water and are therefore known as waterlimes.

The Appalachian Region

Lower Silurian Ridge-making Sandstone.—The oldest, and also the most prominent, Silurian formation of the Appalachian region is a thick, resistant sandstone or quartzite, called the Tuscarora sandstone. This is a white or gray rock, massively bedded, and ranging in thickness to nearly 1,000 feet. It rests disconformably on red beds (Juniata) of the Upper Ordovician. Equivalent beds in eastern Pennsylvania occur with angular unconformity above folded slate (Martinsburg) of Ordovician age. Conglomerate is seen at the base of the Silurian sandstone in many places. The Tuscarora (or Medina) is one of the main mountain-making formations of the Appalachians. The coarse texture of the sandstone and the occurrence of conglomerate, especially toward the east, indicate that Appalachia was rather strongly uplifted at the beginning of Silurian time. Also, the thickness and wide distribution of the sandstone show that erosion of the land must have been extensive in order to supply so large a volume of coarse sandy material.

Middle Silurian.—The next formations, of early Niagaran age, are variable in content and thickness but consist mostly of shale with subordinate amounts of sandstone, thin limestone, and iron-ore beds. The average thickness is between 500 and 1,000 feet. The beds are of marine origin, and, although they appear unfossiliferous, minute fossil shells are abundant in some layers. The fossils and similarity of lithologic features indicate that these beds correspond to the Clinton group of New York.

Iron-bearing beds that occur in this part of the Silurian are of interest, and in places they are of commercial importance. The iron occurs mainly as hematite (Fe_2O_3) which is associated with clay, sand, or limestone. Some of the iron may have been directly precipitated chemically in the shallow sea, but much of it replaces other material, such as limestone particles and fossil shells. A part of the ore occurs in the form of oolite grains. Iron in solution, probably as iron carbonate or sulphate, is precipitated by calcium carbonate and the iron mineral replaces the carbonate. Thus shallow (especially lagoonal) areas containing iron-rich waters would produce iron-bearing deposits, the iron replacing shell

fragments, oolite grains, and other calcareous particles. Where the iron oxide is sufficiently concentrated and abundant, it constitutes an iron ore. The iron-bearing beds are certainly of sedimentary origin, and they indicate an unusual, very interesting condition in this region at the time of their origin.

Upper Silurian.—Formations of Cayugan age are extensive in the Appalachian area, being rather thin or lacking in the south but thickening to more than 1,500 feet in the north. They consist of shale and thin sandstone and limestone beds in the lower part, and prominent fine-grained dark-banded limestone in the upper part. Unfossiliferous red

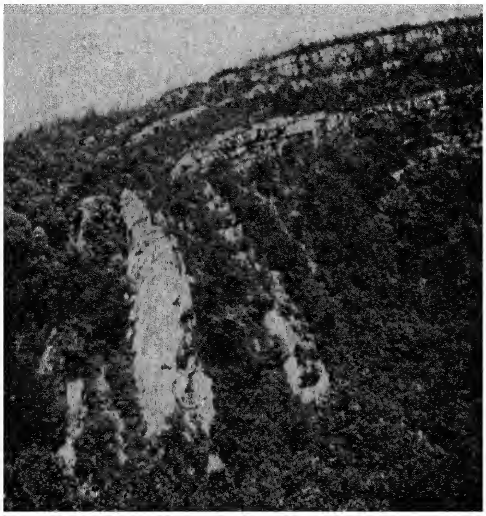


Fig. 71.—Folded Silurian strata (Keefer sandstone) near Clifton Forge, Virginia. (*Charles Butts, U. S. Geol. Survey.*)

shale and sandstone of the lower part of the Cayugan series are most prominent in the eastern parts of the Appalachian trough, and they grade laterally westward into gray shale with some thin limestone beds that contain marine fossils (Fig. 72). The red sediments are apparently of continental origin. The occurrence of upper Cayugan limestone beds above the red beds shows that the Late Silurian sea advanced somewhat toward Appalachia. In Maryland and eastern Pennsylvania this limestone grades upward practically without break into the basal Devonian.

The Continental Interior

Under this heading we may conveniently group the Silurian outcrops of the Mississippi Valley, the Great Lakes region, central Canada, and the Arctic Border of the continent.

Lower Silurian.—The Medinan deposits of the Continental Interior, called Alexandrian, consist mainly of limestone and are relatively thin. The assemblage of fossils is distinctly different from that of the underlying uppermost Ordovician strata and in many places there is physical evidence of the interruption of sedimentation that separates the Silurian and Ordovician systems. For example, rocks of Medinan age (Brassfield) in Ohio overlie a number of different Upper Ordovician formations (Saluda to Elkhorn) and in places they contain pebbles and blocks derived from the older strata. Locally, the Lower Silurian is overlapped by Middle Silurian, which accordingly rests directly on Ordovician rocks.

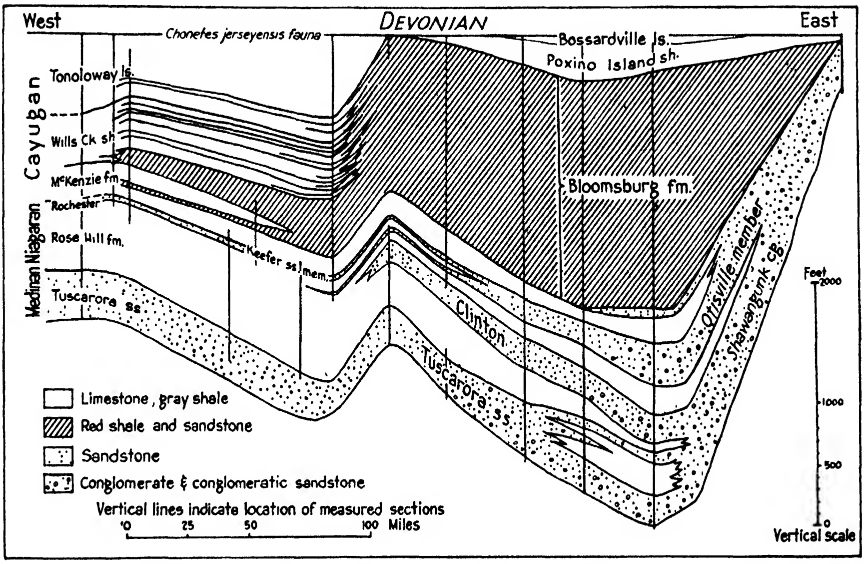


FIG. 72.—Diagrammatic section of Silurian deposits of the Appalachian region in southeastern Pennsylvania, showing especially the westward gradation of unfossiliferous red beds in the Cayugan series into gray shale and limestone. (*Data from C. K. and F. M. Swartz.*)

The Lower Silurian deposits are restricted to the northern and central Mississippi Valley region and a part of Arkansas and southern Oklahoma. The sea was of neither northern nor eastern origin but appears to have come from the south.

Middle Silurian Limestone and Dolomite.—The most prominent formations of Silurian age in the interior region are of Niagaran age. They consist mostly of grayish to yellowish or white magnesian limestone and dolomite in thin or massive layers, the thickness ranging from about 100 to more than 600 feet. In places, especially parts of the Ohio Valley, there are beds of pure limestone and a little shale. The sea in which these beds were deposited was widespread. It was apparently of Arctic origin, as indicated by the nature of the fossils and by the

occurrence of Niagaran limestone on the south shore of Hudson Bay and in the Arctic Archipelago.

Bioherms.—The Niagaran beds of Indiana, the Michigan basin, and some other parts of the Mississippi Valley contain large structureless masses of limestone surrounded by thinly and evenly bedded limestone (or in some cases by massive limestone) which dips steeply away on all sides from the structureless masses, but in a short distance the inclined beds become horizontal. Within the thick unstratified masses of limestone are algae, stromatoporoids,[1] and corals standing in the position of

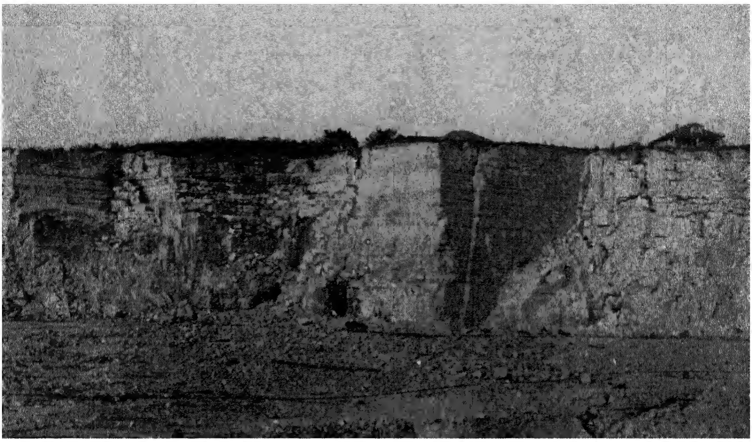


FIG. 73.—Typical Niagaran limestone in quarry at Joliet, Ill. (*Paul MacClintock, in Chamberlin and Salisbury's Historical Geology, Henry Holt & Company.*)

growth, whereas the adjacent stratified rocks contain broken and worn fragments of corals, algal and stromatoporoid deposits, and shells. The unstratified rock masses and the surrounding steeply inclined beds are termed *bioherms* or "reefs." They represent local protuberances of the shallow sea floor that were built by the calcareous secretions of plant and animal communities essentially like those that have made the many modern coral reefs.

Upper Silurian.—Formations belonging to the Cayugan series occur in the Great Lakes region, including Michigan, northern Ohio, and Ontario. They are reported also far to the northwest in the Mackenzie Valley of northwestern Canada. Dolomites, shales, and beds of gypsum and salt are the chief types of rock in this part of the Silurian section.

Salt Deposits.—The area of salt beds in the Upper Silurian exceeds 100,000 square miles, including most of the southern peninsula of Michigan, parts of Ontario, northern Ohio, Pennsylvania, and New York, as

[1] These are lime-secreting colonial invertebrates distinctly related to corals. They are described in Chap. XV.

well as most of the area of Lake Erie and parts of Lake Huron and Lake Michigan. According to borings, the maximum thickness of rock salt is a little over 600 feet, reported near Detroit and Alpena, Mich. A few miles south of Syracuse, in central New York, the salt is more than 318 feet thick. In parts of this region, as in central Michigan and northern Pennsylvania, the salt formation is so deeply buried that it has not been penetrated by wells.

If we estimate that the average thickness of the salt is 100 feet, which is probably conservative, computation shows that there is more than a hundred million cubic yards of salt in the whole basin—a stupendous amount weighing more than 185 million tons. It would require the evaporation of about 8,000 feet of sea water, covering all of this area, to

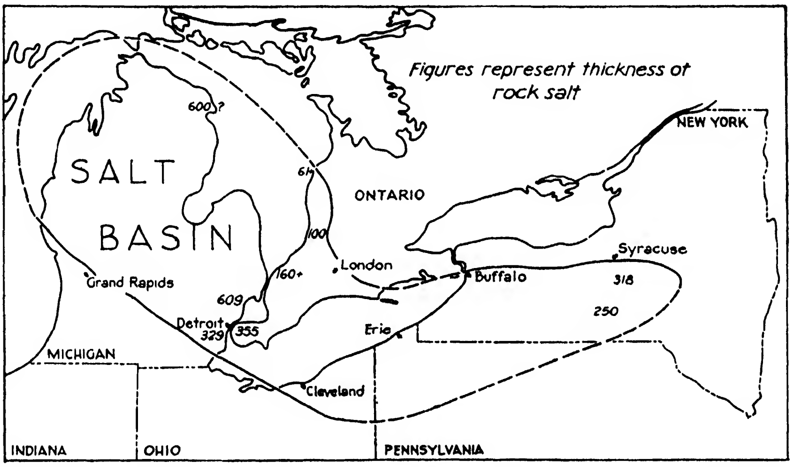


FIG. 74. Map showing approximate outline of the Silurian salt deposits in the Michigan-New York region.

supply this quantity of salt. We may say with some confidence that the waters in which the salt was precipitated were probably never even one-tenth of this depth. The Cayugan salt was not formed by the evaporation to dryness of a sea cut off from the ocean, like the Caspian of the present day, for if this had been so, we should find with the rock salt large deposits of potash and magnesian compounds that are contained in sea water and that are more soluble than ordinary salt. These soluble potash and magnesian minerals are not known in the region. We must conclude, then, that the salt sea was periodically or continuously replenished with salt water coming from a connection with the open ocean. This connection must have been too restricted to permit free circulation but sufficient to allow compensation of the lowering of level in the inland sea due to evaporation. Comparable conditions could exist today in continental seas like Hudson Bay or the Baltic if the climate in these regions were sufficiently hot and arid. It is necessary, however, that

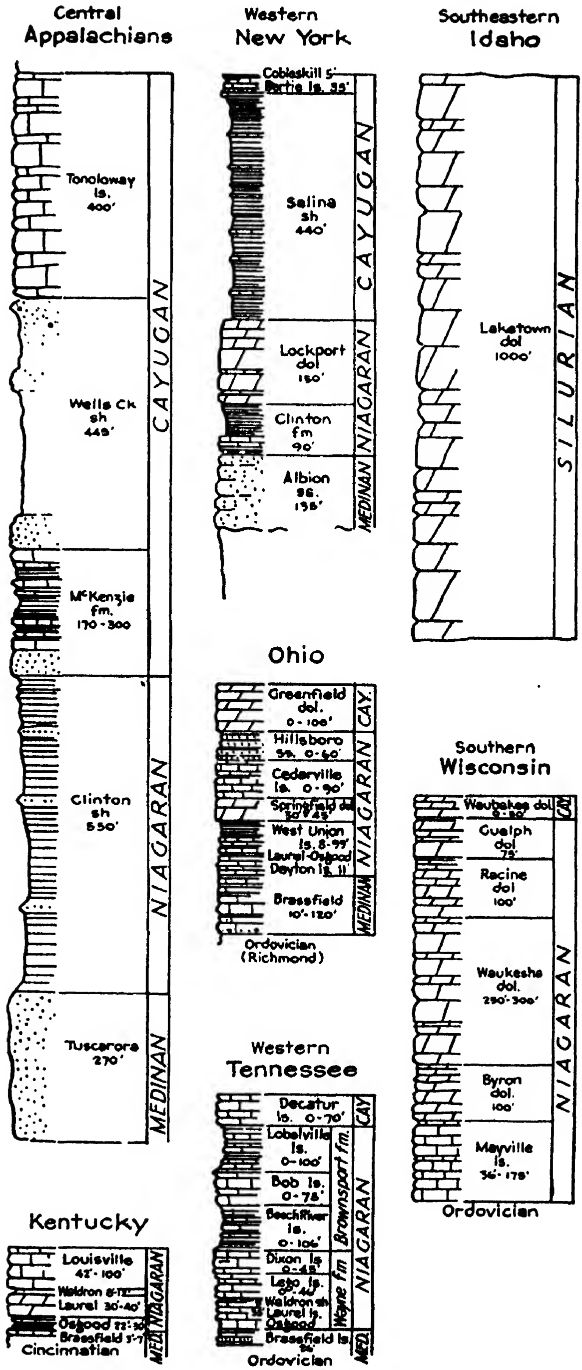


Fig. 75.—Some typical sections of the Silurian system.

the passageway leading to the salt basin should be shallow enough to prevent drainage of the heavy brines from the basin into the outer sea.

The suggestion has been made (Grabau) that a major part of the Cayugan salt may have come from leaching of salt from the large surrounding area of recently formed marine sediments. The pore spaces in these sediments would, of course, be filled with sea water, and under proper conditions salt derived from this water could be carried into an inland sea. The Great Salt Lake is a highly saline water body because salt carried into it by streams is concentrated by evaporation that exceeds precipitation. Quantitative comparison of the salt that might be derived from leaching of Middle Silurian marine formations and the salt beds of the Cayugan series indicates that the suggested source is considerably too small for the observed deposits. It is none the less possible that some of the salt may have been obtained from this source.

The Cordilleran Region

Silurian rocks have been reported in Idaho, Utah, Nevada, and British Columbia, but they have been little studied. Most of western North America seems to have been land during Silurian time.

SILURIAN DEPOSITS OF OTHER CONTINENTS

Silurian formations are widespread in Europe. They rest unconformably on Ordovician rocks in central England, Wales, and part of France. The nature of the sediments varies greatly in different places and in different parts of the system. As in America, some of the Upper Silurian beds appear to be of continental origin. Peculiarities in the distribution of certain groups of fossils, and the presence of unconformities in various sections, show changes in the distribution of the Silurian seas during the period. Outside Great Britain, the most important areas of Silurian rocks are found in Bohemia, Germany, France, northwestern Russia, Scandinavia, and islands of the Baltic, especially Gotland.

In Asia, the Silurian is known in Siberia, China, Turkestan, Burma, and the region of the Himalayas. Rocks of this age extend also across parts of Australia and New Zealand. The Silurian is represented in northern Africa and in the Brazilian portion of South America.

PHYSICAL HISTORY OF SILURIAN TIME

Medinan Epoch.—The early part of Silurian time is marked by an uplift of the Appalachian borderland which caused west-flowing streams to carry large quantities of grit and sand into the adjacent geosynclinal area. Much fine sediment was probably also carried toward the lowland of the Continental Interior but, if so, it was mostly transported beyond the belt in which the sand was deposited and it is now concealed by younger Paleozoic rocks in the western Appalachian and Allegheny Plateau region. Shallow clear seas in which limestone was deposited were present during part of this time in the Continental Interior, reaching

eastward to Ohio, southwestward as far as southern Oklahoma, and probably northward far into Canada.

Niagaran Epoch.—The medial part of the Silurian period is characterized by widespread marine inundation, the deposits formed in most of the submerged area being limestone and dolomite, which denote clear but not necessarily deep water. In the early part of this epoch (Clinton time) a sea which appears to have been connected with the Atlantic occupied the Appalachian trough and spread westward as far as Indiana. Several hundred feet of beds, consisting mostly of shale, were derived from the adjacent Appalachian land mass but locally, as in eastern New York, the deposits consist of coarse sand and conglomerate. Red color,

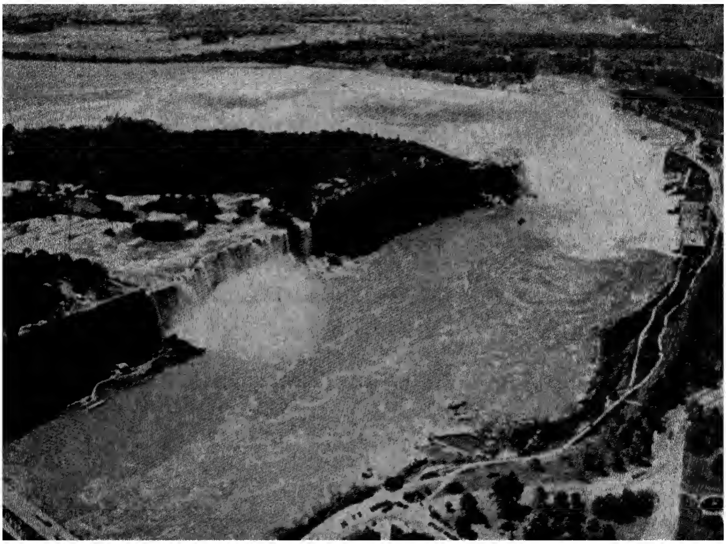


Fig. 76.—Niagara Falls, formed by resistant Middle Silurian dolomite. (*From International Geol. Congress Guidebook* 4, *by permission of M. J. Washburn.*)

due to abundant iron oxide, distinguishes parts of these deposits of the Appalachian region, and in places the iron is so concentrated as to make iron ore. Excepting only some of the sand and conglomerate, all of the strata appear to be of marine origin. In this earlier part of the Niagaran epoch, part of the central and all of the western Mississippi Valley region appear to have been emergent, but in Wisconsin and Michigan there are dolomitic beds deposited in a sea that came from the north and apparently was not connected with the Appalachian area.

In the later part of the Niagaran epoch (Lockport time) there was a marked change in conditions, for deposits of this age are not known in the Appalachian region, while they are exceedingly widespread in the Mississippi Valley and the country to the north. There is evidence that

this sea also invaded northern Europe. Fossils in the upper Niagaran deposits of the Mississippi Valley, in remnants of these rocks in central and northern Canada, and in Middle Silurian formations of the Baltic region of Europe are remarkably alike. This similarity includes some very strange and peculiarly specialized organisms that certainly did not originate simultaneously and independently in these widely separated areas. The deposits consist mostly of dolomite; there is a little limestone but almost no shale. The waters were clear and probably moderately warm, for reefs (bioherms) of corals, algae, and stromatoporoids are found in many places. Some of the southern Silurian deposits of this time, in Oklahoma, Arkansas, and Tennessee, contain several kinds of fossils that are not known in the north and it is believed that these deposits are due to a temporary invasion of a sea from the south.

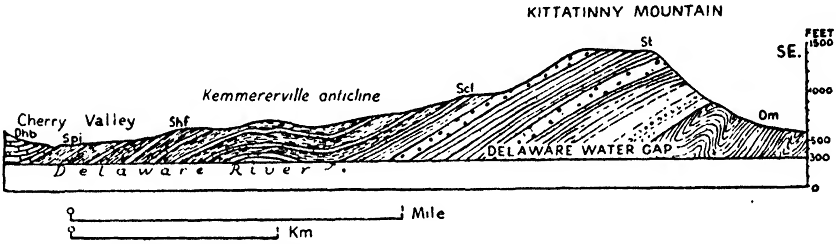


FIG. 77.—Section of Silurian and associated rocks in northern New Jersey. Kittatinny Mountain is formed by the resistant Tuscarora sandstone of Lower Silurian age. (*From International Geol. Congress Guidebook 7, after Bradford Willard.*)

Cayugan Epoch.—In contrast to the Niagaran epoch, early Cayugan time is distinguished by a restricted sea. Most of the area of Middle Silurian dolomite deposition became dry land, while the Atlantic sea again came into the northern part of the Appalachian trough. The red and gray unfossiliferous shale in the New York and eastern Appalachian region, and sand which at places occurs with these, is interpreted as continental in origin, representing soil materials that were brought from the land by streams, or possibly in part blown by the wind. Prevalent red color shows the thorough oxidation of iron compounds. From New York westward to Michigan the accumulation of thick salt beds points to a dry arid condition. The dwindled water body that covered the area where salt beds now occur probably had restricted connections with the open sea in the east and there may have been indirect connection with the sea in the northern part of the Appalachian trough. Later, the connection with the outer ocean waters was widened and the salt content of the interior sea became more nearly normal. Dolomite and limestone beds containing marine faunas were deposited.

Climate.—For the same reasons that were advanced in discussing climate of Ordovician times, it is probable that the Silurian period was characterized by generally warm, fairly uniform climatic conditions.

The seas were widespread and the adjacent lands were low-lying, except in Appalachia during the early part of the period. Reef-building corals were widespread in the clear lime-depositing inland seas, and fossils from the far north are practically the same as those from the central United States. The salt beds and associated sediments of early Cayugan time in the Michigan-New York area point to aridity in this region. There is some evidence of glaciation in parts of the Silurian of Alaska, but this is local, and if glaciers were existent they were probably not extensive or of long duration. Appearance of divergent climatic indications in different regions, and representing possibly different portions of time as long as a geologic period, should not be regarded as inhar-

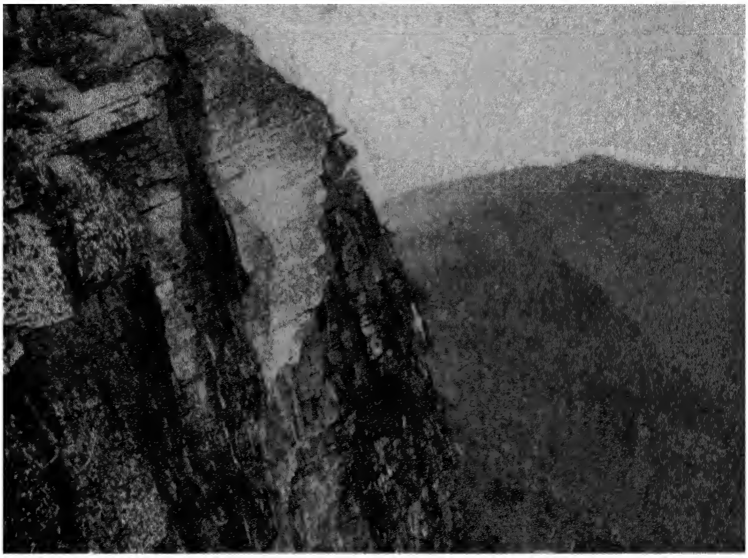


FIG. 78.—Front of Shawangunk Mountain, southeastern New York. The cliff-forming rock is the Shawangunk formation of Silurian age, about 600 feet thick. (*Florrie Holzwasser, Barnard College.*)

monious. Climatic variation rather than extreme uniformity should normally prevail.

Close of the Period.—Discussion of the upper boundary of the Silurian in North America has brought out the fact that there were no great geographic changes at this time that serve to separate the Silurian period sharply from the Devonian. The continent was generally emergent but nowhere in the United States is there evidence of mountain-making at this time. This is not the case, however, in other regions. The close of Silurian time brought to Europe one of the great mountain-building epochs of its geologic history. The roots of these mountains are now traced along the northwestern margin of the continent in Scandinavia and the highland of northwestern Scotland. The rocks are very pro-

foundly folded and faulted, indicating that the Silurian mountains, which have been called the *Caledonian Mountains*, were probably once comparable in magnitude and grandeur to the Alps. Great masses of rock were pushed along some of the thrust faults for dozens of miles. Associated with this deformation of the sedimentary rocks, there was intrusion of granites and related igneous rocks on a huge scale.

Recent explorations in the Arctic show that the northern edge of North America was greatly disturbed and crumpled at this time. The Silurian mountains of this region have been traced along the north coast of Greenland, in Ellesmereland, and in northern Alaska, trending in a general northeast-southwest direction. Lesser mountain-making movements took place at the end of Silurian time also in Asia, Australia, South America, and northern Africa.

The mountain-building and attendant biologic changes at the close of Silurian time may be considered as dividing the older from the younger part of the Paleozoic era. The Caledonian disturbance was more profound and widespread than any that had occurred since the beginning of Paleozoic time. The Silurian and older geologic periods are generally characterized by the dominance of marine life consisting mostly of invertebrates. The later Paleozoic has also abundant marine life but it is characterized by the first appearance of land plants and animals. We may, therefore, regard the Silurian as the closing part of the Early Paleozoic subera.

ECONOMIC RESOURCES

The chief materials of economic importance obtained from Silurian rocks are salt, oil and gas, iron ore, glass sand, cement rock, and stone for highway and construction purposes.

Salt in the Upper Silurian Michigan-New York area is produced by underground mining and by brine wells. In the production of salt from wells, water is forced to the salt-bearing beds, allowed to dissolve the salt, and then pumped back to the surface, where the brine is evaporated in vats. Michigan is the largest salt producer in the United States but a portion of the salt comes from post-Silurian formations; next is New York, and then Ohio. The annual total yield from the Silurian salt beds is valued at 15 to 20 million dollars.

Oil and gas are obtained from Lower Silurian rocks in a belt that crosses Ohio from north to south a little east of the center of the state. Some oil production is also obtained from Middle Silurian limestone in Kentucky. The known quantity of oil and gas in Silurian formations, however, is vastly less than in the Ordovician.

Iron Ore.—Outcrops of the Clinton iron ore extend across New York state and along the Appalachian belt to Alabama. The ore contains up to 50 per cent metallic iron and formerly was worked at many places. At present the iron is mined extensively only in the Birmingham district of Alabama, where conveniently adjacent coal deposits encourage development of a great steel industry which serves the southern market. The chief iron-ore bed near Birmingham is 16 to 18 feet thick and a short distance beneath it is another bed 4 or 5 feet thick which is mined in places.

Glass Sand.—Clean, white sandstone of Lower Silurian age is mined extensively for glass manufacture in Pennsylvania and Maryland.

Cement Rock.—Impure limestone in the Upper Silurian of New York, Ohio, Indiana, Michigan, and Ontario has the properties of a natural cement rock and it has been extensively quarried. Portland cement, however, is made from ordinary limestone mixed with the proper proportion of clay shale.

Stone.—Silurian dolomite is extensively quarried in many places, especially near Chicago, for the purpose of securing stone for construction purposes, chiefly concrete in buildings and highways.

SUMMARY

The Silurian system rests unconformably on Ordovician beds and, excepting part of the Appalachian district, is overlaid unconformably by Devonian or younger formations.

The oldest division of the Silurian (Medinan series) consists of limestone in the Mississippi Valley, but in the Appalachians there is a thick, very resistant quartzitic sandstone that makes mountain ridges.

The Middle Silurian (Niagaran series) is characterized chiefly by magnesian limestone and dolomite formations that cover most of the Mississippi Valley and Great Lakes region and extend northward to the Arctic Circle. An interesting feature of part of these calcareous deposits is the occurrence of well-defined reefs (bioherms) composed of corals, algae, and stromatoporoids. New York and the Appalachian Mountain area contain marine shaly beds, part of which are red, and a persistent iron-bearing zone which is sufficiently rich in many places to be classed as iron ore. The Niagaran rocks of eastern New York and part of Pennsylvania consist of thick, resistant conglomerate. Rocks of late Medial Silurian age seem to be absent in the southern Appalachians.

Upper Silurian rocks (Cayugan series) consist of normal marine limestones, sandstones, and shaly beds in the Appalachians, and of red and gray mostly unfossiliferous shale, gypsum, and salt beds in New York and the eastern Great Lakes area. The salt beds extend over about 100,000 square miles and have a maximum thickness of more than 600 feet.

Outstanding features in the history of Silurian time in North America are (1) continental sedimentation in the Appalachian area during the Early Silurian epoch, an outwash of coarse sand being spread westward from Appalachia, (2) deposition of red sediments and iron ore in the Appalachian region in early Medial Silurian time, (3) a great Arctic invasion that covered the central and northern parts of the continent in later Medial Silurian time, making limestone and dolomite beds that in places contain numerous reefs, (4) restriction of the interior sea to the eastern Great Lakes region in the Late Silurian epoch (or possibly the formation of a huge salt lake), and continued evaporation leading to deposition of gypsum and thick salt beds, (5) presence in the Appalachian trough of normal marine conditions near the close of Silurian time, persisting with practically no break into the Early Devonian, and (6)

important mountain-building along the northern border of North America at the close of the Silurian, which constitutes part of the Caledonian disturbance that is so prominently shown in northwestern Europe.

The climate of Silurian time was probably warm and generally equable, but arid conditions appear to have prevailed in the Michigan-New York region during the late part of the period. Glaciation may have occurred locally in Alaska.

The chief economic products of Silurian rocks are salt, natural gas, and iron ore.

CHAPTER XIV

THE NATURE OF FOSSILS

The presence in sedimentary formations of abundant well-preserved remains of plant or animal life is an exceedingly important feature in the delineation of earth history. The Early Paleozoic rocks are the first that in certain layers and in many places contain abundant evidence of life. It is desirable, therefore, to introduce at this point some consideration of the essential characteristics of fossils, the conditions necessary for fossilization, and factors governing the practical usefulness of fossils in deciphering the geologic record. Classification of the different kinds of animals and plants is also outlined briefly. The following chapter describes the classes of organisms that are important in the Early Paleozoic periods and the general nature of the known faunas of each period.

CHARACTERISTICS OF FOSSILS

Fossils are the remains or traces of animals or plants, in which the form, and in some cases the structure, is preserved in rocks. The word comes from the Latin *fossilis*, meaning something dug out of the earth.

In ancient and medieval times, most men regarded the fossil sea shells, teeth, bones, or leaf imprints that were discovered in rocks as freaks of nature or the ineffective creative efforts by some plastic force within the earth. Later, they were accepted by some students as the actual remains of life that existed before the flood of Noah, death and entombment in the sediments resulting from the Great Deluge.

More accurate geologic observations led to the discovery, about the beginning of the last century, that the fossils of a given bed or group of beds were characteristic of it and that there were persistent, readily distinguishable differences in the fossil organisms of other rock layers. Since strata containing a multitude of marine shells, and thus evidently representing deposits made in the sea, were found far inland from present seacoasts, even at the summits of mountain ranges like the Alps and Apennines, it appeared that great changes or catastrophes must have affected the seas and lands of the past. Thus was developed the idea that from time to time in past earth history there were general upheavals that destroyed existing life, and following these there were new creations of somewhat different organisms. The fact that some animals and plants have persisted with little or no change, the very clear relationship between successive natural assemblages of animals (faunas) and natural

assemblages of plants (floras), and the steady advance in complexity and specialization of different forms of life from earlier to later times are evidences opposing this view of catastrophic change. Especially since Darwin's time, the theory that all existing forms of life have descended with gradual alteration from successively earlier types has been found to agree entirely with the record of life as preserved in the rocks. The theory of organic evolution accords also with the guiding principle of geology, which is that nature's laws operate uniformly (uniformitarianism).

Requisites of Fossilization.—Normally, the death of an animal or plant is followed quickly by decay which destroys the tissues and eventually obliterates all traces of the organism. If, however, the attack of

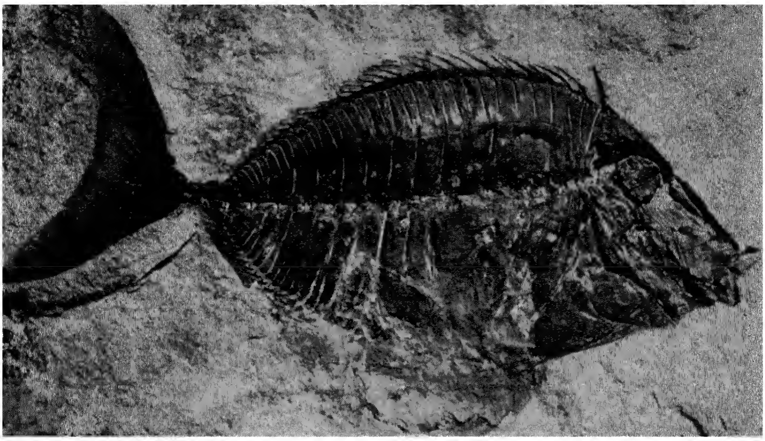


Fig. 79.—A fossil fish (*Zebrasoma*) from the Green River lake beds of Eocene age, southwestern Wyoming.

The bones, teeth, and fin rays of the fish are well preserved, and the outline of the body is clearly shown by carbonaceous residue. The fish lies on its side on a bedding plane of the shale, and it has been greatly flattened by compaction of the sediments. (*American Museum of Natural History.*)

putrefactive bacteria and other agencies of disintegration is largely or entirely prevented, remains of the organism may be preserved. Thus mummies may be made by proper embalming and spicing. The very dry air of a desert or cave may desiccate and preserve an animal. In a different way, the same ends are served when an organism is frozen solidly in ice, as is illustrated by rhinoceroses and mammoths entombed for thousands of years in the frozen tundras of northern Siberia. Parts of these animals are now preserved in museums, and it is recorded that the flesh of one specimen was eaten by men and dogs. Various insects, preserving every detail of structure and color, have been found in amber, which is the fossilized resin of conifer trees. Covering by water or burial in fine water-saturated sediments does not ordinarily prevent bacterial decay of the soft tissues but commonly results in preservation of harder parts.

Animals like the jellyfish, sea anemone, many protozoans, sponges, and others that lack hard parts, and plants like the majority of seaweeds, mosses, lichens, and all others lacking resistant cell structures are ill-adapted for fossilization, because complete disintegration follows death very rapidly. Accordingly, such forms of life are rare or absent among fossils.

In general, then, we may set down two chief requisites for fossilization: (1) the organism must be buried quickly in some protecting medium, and (2) it must possess some sort of hard parts. Under these conditions, the hard structures, such as skeletons and shells, may be preserved as fossils.

Environmental Factors in Fossilization.—The conditions surrounding a living plant or animal, that is, its environment, are significant in connection with the study of fossils, (1) because these conditions indicate the probability or improbability of fossilization, and also (2) because fossils furnish evidence in varying degree of definiteness as to the environment in which the fossilized organism lived. To illustrate: the conditions in a shallow sea are generally very favorable for fossilization, and the occurrence of fossil shells representing kinds of animals that are known to live only in shallow marine waters furnishes evidence also that the sediment containing the fossils was deposited in a shallow sea. In other words, each kind of plant and animal is best adapted, and in many cases is sharply restricted, to a certain environment. This fact, on the one hand, affects its chance to become a fossil, and, on the other, if fossiliza-

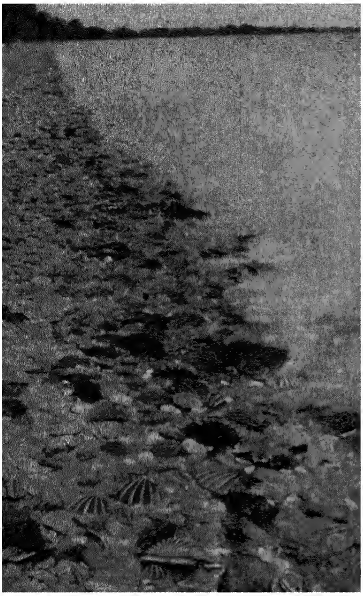


FIG. 80

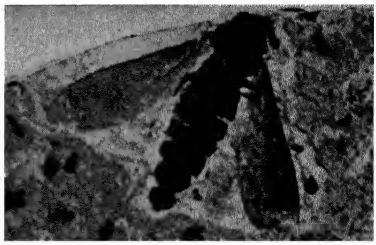


FIG. 81.

FIG. 80.—Shells thickly strewn along a beach on Chesapeake Bay.

Shell-bearing organisms are abundant on many parts of the shallow sea bottom, and the shells when buried by sediment may become fossils.

FIG. 81.—A fossil fly (*Megacosmus*) from Miocene lake beds near Florissant, Colo.

The finely laminated sediments consist largely of volcanic ash that sifted from the air and was brought by rain wash and streams into the lake. Beautifully preserved leaves are common and insects are numerous in this deposit. The fossil here shown is flattened to a thin film. (*T. D. A. Cockerell, American Museum of Natural History.*)

tion does take place, the remains of the organism not merely indicate former existence of life but throw light on the surroundings in which it lived.

Fig. 82.—A "bone bed" containing skeletal remains of scores of rhinoceroses and other mammals occurs in the Miocene deposits of northwestern Nebraska. The upper view shows a quarry in the bone bed at Agate Springs, Nebr. The lower figure shows part of a slab with the matrix sufficiently removed to show the accumulation of bones as they occur in the bed. (*American Museum of Natural History.*)

The chances of preservation of an organism as a fossil are naturally greatest in the seas and oceans because conditions favor slow disintegration and fairly rapid burial in the muds and sands of the sea bottom. Generally speaking, marine formations are abundantly fossiliferous, but because some parts of the sea bottom (for example, areas of shifting sands)

are not favorable for habitation, and because organic remains may be destroyed by scavengers, by pounding of waves, or in other ways, not all marine strata contain fossils.

On the lands, best opportunity for fossilization is found in lakes and swamps, but deposits in these places are much more likely to be obliterated by erosion than in the case of marine formations. Famous fossil-bearing lake deposits are the Green River beds in Wyoming and the

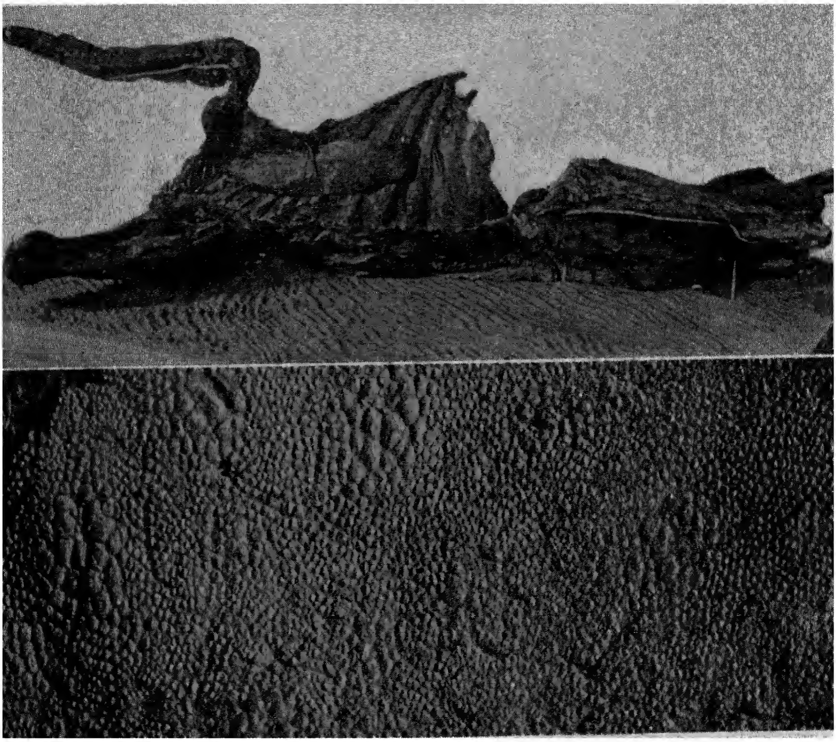


FIG. 83.—Fossil remains of a duck-billed dinosaur (*Trachodon*), one of the giant reptiles of Mesozoic time that lived in the western United States.

The upper figure shows the skeleton with bones articulated and covered by the stretched, dried skin just as it was discovered in Cretaceous sandstone. After death, the animal was partially "mummified" in the dry air and buried by drifting sands. The lower figure is a "close-up" showing the appearance of part of the skin. (*American Museum of Natural History.*)

Florissant beds in Colorado, both of Tertiary age. These contain beautifully preserved fishes, insects, fresh-water shells, and the leaves and twigs of land plants that were blown by winds or carried to the lake by streams. The plants associated with peat and coal beds are fossils of swamps and marshes. Some of these plant fossils show delicate structures in wonderful perfection.

There are also fossils of the rivers and creeks. These are found especially in areas of alluvial deposition, along flood plains, fans, and basin fillings. Here occur the skeletal remains of innumerable large and small

animals of the land that were drowned, mired, caught in quicksand, or otherwise buried.

The tundras of the far north, areas of water-soaked ground that are soft and treacherous in the short season of relative warmth but frozen solidly most of the time, have yielded well-preserved carcasses of extinct rhinoceros and mammoth, but comparable fossils of older geologic time are not known.

Deserts are not thickly inhabited, but fossils are found rarely in sandy deposits of ancient deserts. Such appear to be the mummy-like remains of one of the Cretaceous giant reptiles (dinosaurs) found in

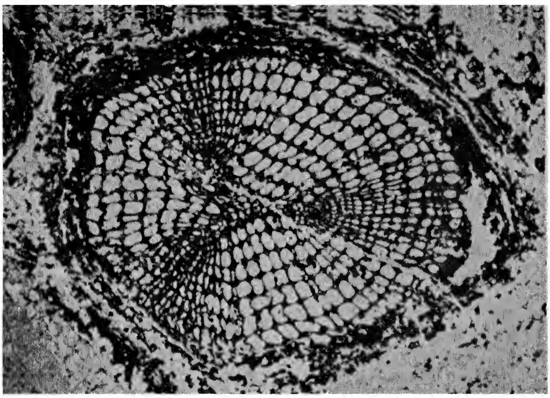


FIG. 84.—Cross-section of the stem of a Pennsylvanian plant (*Sphenophyllum*) from Illinois, showing well-preserved cell structure. The original cell walls were replaced in submicroscopic particles by calcium carbonate during the process of fossilization. (*A. C. Noé, University of Chicago.*)

Wyoming, the dried and shrunken skin stretched tightly about the skeleton.

Eruptions of volcanic ash have been responsible in many cases for the accidental burial of numerous animals and plants. The suffocated organisms are likely to be preserved as fossils. In this way the superposed forests of standing trunks in Yellowstone Park have been formed, and also the many fine mammal fossils in the John Day basin of Oregon. In somewhat similar fashion the Roman cities of Pompeii and Herculaneum were buried and preserved under volcanic materials from Mount Vesuvius Volcanic ash may sink down in lakes or in the sea and smother aquatic life, leading to the formation of fossils.

Modes of Preservation.—The hard parts of an animal or the woody tissues of a plant may, under proper conditions, be preserved unaltered in the sediments that bury them. In the majority of cases, however, especially in all older fossils, important changes have occurred. Shells composed of calcium carbonate may be made more dense by infiltration of calcite deposited by ground water, and in some cases, as commonly

among echinoderms, there is a crystallization that develops the cleavage and all other properties of the mineral calcite. Replacement of the original hard parts by some other mineral, in submicroscopic particles, may result from substances dissolved in ground waters. Thus, replacement by calcium carbonate is termed *calcification;* by silica, *silicification;* and by iron pyrite, *pyritization.* Less commonly, other minerals may form the replacing substance. In all cases of replacement particle by particle, the microscopic structures of the hard parts are preserved, though chemical composition is altered. In the case of many plants and a few animals, slow decay under water results in concentration of carbon, and the fossil consists of a film of carbon showing more or less distinctly the form and structure of the original tissues. This is termed *carbonization.*

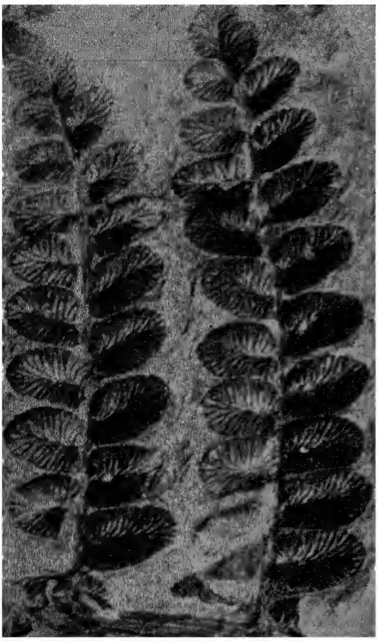


FIG. 85.—Portion of a fossil fern (*Neuropteris*) from Lower Pennsylvanian rocks of Alabama.

The outline and the vein pattern of the leaflets are clearly impressed in the fine-grained rock, and there is also a carbonaceous residue of the original plant matter. (*Charles Butts, Alabama Geol. Survey.*)

After burial in sediments, the hard parts of an organism may be removed completely by solution, leaving merely the *mold* of its form in the surrounding rock. In cases where the enclosing sediment is only partially consolidated, the cavity of the mold may be closed by pressure. Commonly, however, the mold is not squeezed together and, when changing conditions result in the filling of fossil molds by some foreign mineral substance, this filling, just like metal poured into a foundry mold, may be termed a *cast.* Fossils are most commonly preserved as molds in sandstones and dolomites. It is interesting to observe that many calcareous shells, including especially those of the mollusks, are composed largely of the mineral aragonite, which is very readily soluble, while others, such as belong to most of the brachiopods and bryozoans, are composed of calcite, which is much less readily soluble. Therefore, in many instances the aragonite shell substance is preserved as a replacement or has been removed entirely, leaving a mold, while the calcite shells are essentially unaltered.

Color ornamentation, which adds interest to collections of modern shells, is mostly lost in the process of fossilization. Occasionally, however, indication of pigmentation is preserved in dark markings on parts

of the fossil. Thus, by the nature of color distribution, it is possible to determine the proper orientation of the chambered tube of the straight-shelled cephalopod *Orthoceras*. Traces of coloration are most commonly found among gastropods.

Indirect evidence of the existence of organisms is not uncommon. Among these may be mentioned the fossil tracks of land animals, the

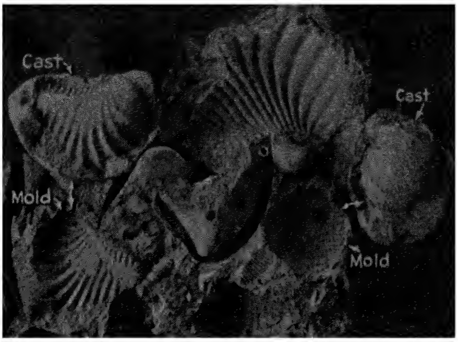


FIG. 86.—Fossil molds of some Mesozoic shells in fine-grained sandstone. The original shell substance has been removed by solution, leaving only external and internal impressions to show the form of the shells. At the right and upper left are casts made by squeezing a plastic substance into some of these molds. (*U. S. National Museum.*)

trails or borings of worms and other invertebrates, and coprolites (fossil excrement). The gizzard stones of certain ancient reptiles which may be identified by their form, surface polish, and manner of occurrence in rocks, and the stone implements or weapons of prehistoric man may also be regarded as indirect fossils.

FIG. 87.—Tracks of a Permian amphibian from the Coconino sandstone, Grand Canyon of the Colorado, Arizona. This specimen is really a "negative" of the footprints, being the under side of the slab that covers the original track-marked sand. (*C. W. Gilmore, U. S. National Museum.*)

Compaction of sediments by the weight of overlying rocks is likely to produce a flattening of the contained fossils, and this is especially noteworthy in shale, one of the most highly compactible types of sediment. Other pressures, such as those to which mountain uplifts and regional metamorphism are due, may distort or even obliterate fossils contained in the sediments.

Index Fossils.—In varying degree, practically all fossils afford indication of the geologic age to which they belong. Some kinds, however, persisted essentially unchanged for a very long time, while others were very short-lived. Among the brachiopods, *Leptaena rhomboidalis* (or its almost indistinguishable allies) ranges from Ordovician to basal Mississippian strata, but *Hypothyridina cuboides* is restricted to a single horizon at the beginning of the Upper Devonian. In precise correlation of fossil-bearing strata it is important to recognize and differentiate species that appear only in a given bed, or a short succession of beds, for the occurrence of the same species elsewhere points to equivalence in age of the containing strata. Such fossils may be termed *index fossils.* In general, a fossil species is the best index of geological time if it is (1) restricted to a narrow vertical range, (2) widely distributed horizontally, (3) abundant, and (4) distinctive in character, so as to permit ready and definite identification.

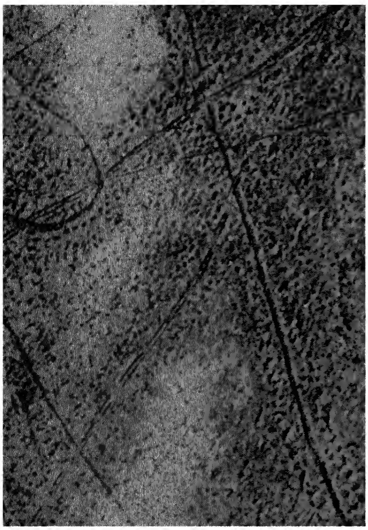
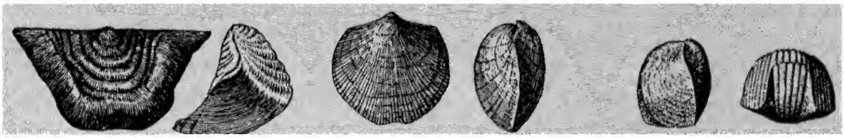


FIG. 88.—Trails of crustaceans called trilobites from Upper Cambrian sandstone, New York. (*C. D. Walcott.*)

Completeness of the Fossil Record. The conditions affecting fossilization that have been described make evident the conclusion that only a small part of organisms existing at any one time are likely to be preserved as fossils. This is especially true of life on the land. Of the organisms that have hard parts and are quickly buried, a large number are likely to be destroyed by action of dissolving ground waters, by metamorphism, or by erosion of the containing sediments. It is obvious, further, that only an insignificant portion of the fossils that have been preserved are accessible to man, for many are buried hundreds or thousands of feet below the earth's surface or beneath the sea. As regards fossiliferous formations that occur at the surface, the nearly complete cover of soil and vegetation or, in places, of glacial drift largely conceals the stratified rocks, and in exposures where fossils may be found, only a small portion can have been collected. These considerations lead us to the conclusion that knowledge of ancient life must be exceedingly incomplete, and in a sense that is true. As Huxley has said, "many paragraphs, some chapters, and a few whole volumes are missing from the record of life on the earth."

In spite of all these conditions that contribute to a fragmentary record of life, the fossils known to science are well distributed among the different classes of organisms. Practically all of those that have hard parts



Leptaena rhomboidalis (Ordo-Miss) Atrypa reticularis (Sil.-Dev.) Hypothyridina cuboides (base U Dev.)

FIG. 89.—The brachiopod *Leptaena rhomboidalis* existed practically unchanged from middle Ordovician to early Mississippian time and in many formations deposited during this long interval it is common. *Atrypa reticularis* is another "Methuselah" among brachiopods. *Hypothyridina cuboides*, on the other hand, is narrowly restricted to basal strata of the Upper Devonian, and it is a good "index fossil" of this horizon. (*Winifred Goldring, New York State Museum.*)

and a few that do not, are represented by fossil remains. There are several "missing links" connecting groups that are now very unlike and

FIG. 90.—A cluster of Devonian trilobites (*Phacops*), an extinct type of marine crustacean that was abundant in much of Paleozoic time. The rock matrix has been partly cut away so as to reveal the fossils. (*U. S. National Museum.*)

showing clearly in these cases how evolutionary changes have progressed. In the aggregate, a remarkably clear picture of the gradual development of life is available to us.

KINDS OF PLANTS AND ANIMALS

Nearly a million different kinds of living plants and animals have been observed and described by man, and the number of known fossil types exceeds 100,000. In variety of form and complexity of structural organization, the kinds of life range from microscopic one-celled organisms of varied form, like the bacteria and protozoa, to the most highly specialized flowering plants and to man. It is not possible or necessary for us to consider exhaustively this voluminous record of life, but, in order to understand the general course of its development and to grasp

FIG. 91.—Dinosaur skeleton partly excavated but still in place where it was discovered Belly River (Cretaceous) beds of Alberta, Canada. (*American Museum of Natural History.*)

the evolutionary significance of distinctive life forms that are known from each part of geologic time, we must know the outstanding characters of the main groups of plants and animals. These will be taken up briefly in connection with our survey of the main forms of life in the major divisions of geologic time.

Classification of Organisms.—Prior to the time of Linnaeus, whose epoch-making work Systema Naturae appeared in the year 1735, the comparatively small number of described animals and plants was designated either by some simple common name or, in many cases, by a long and cumbersome descriptive title. Linnaeus introduced the binomial nomenclature which now has universal scientific use. The group (genus) to which an animal or plant belongs is designated by the first name, generally derived from the Greek, and the individual kind (species) by the second name, generally derived from the Latin. *Felis*

domesticus, the common cat; *Felis leo*, the lion; *Felis concolor*, the puma, and a number of others are all species of the genus of cats. Obviously they are all closely related to one another. *Smilodon* and *Hoplophoneus* are extinct genera of cats characterized by unusually elongated saber-like canine teeth, and differing in other respects from modern *Felis*, but we group together all of the cats in the family Felidae. Thus, in ascending scale of comprehensiveness, there are species, genus, family, order, class, phylum, and kingdom. All animals and plants may be classified according to this plan, but, because of differences in knowledge or judgment as to the relationship and points of difference between organisms, there is by no means complete accord among biologists on the subject of classification.

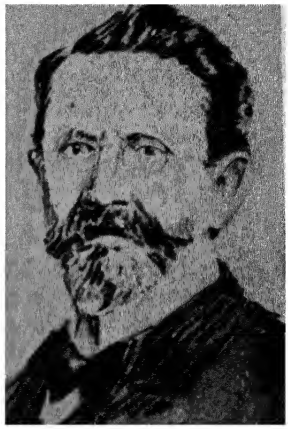


FIG. 92.—Karl von Zittel, author of the great work on fossils, "Grundzüge der Paläontologie."

A species is actually not a fixed and definite thing, ordered for man's convenience in pigeonholing the forms of life. Under man's own control, remarkable changes have been effected in many kinds of plants and animals. Differences in environment or geographic isolation may produce very marked alteration in the character of species, and yet completely intergrading types often may be found. Innumerable examples of gradual but distinct change in form and structure with lapse of time are furnished by the records of fossils in successively superposed beds. Thus it may be difficult to decide what should be regarded as the limiting characters of a species. Because it is very important to the paleontologist to recognize, if possible, every distinction between the forms of life that are preserved as fossils in each formation, there is a growing tendency to regard as distinct species each type of organism that shows persistent recognizable differences, even though in some cases the distinctions are not very great. Some authors use the term varieties for these lesser differences in form that are presumably connected by intergradation. While it is recognized that there is a certain measure of unavoidable artificiality in any system of classification, it is most important to realize that life on the earth has been continuously changing more or less slowly, and that present plants and animals represent simply the end products of all this change.

The main plan of organization of the plant and animal kingdoms, omitting certain divisions that are unimportant as fossils, is represented in the following tabular outline. Divisions that are extinct are marked by an asterisk (*).

Main Divisions of the Plant and Animal Kingdoms

Plants

Thallophyta, cellular tissue plants without distinction of root, stem, or leaf.
  Schizophyta, one-celled plants, bacteria.
  Algae, seaweeds, diatoms.
  Fungi, mushrooms, molds. No importance as fossils.
Bryophyta, plants with leafy stems, the mosses and liverworts. No importance as fossils.
Pteridophyta, plants with root, leaf, and woody-fiber stem, the ferns.
Arthrophyta, plants with jointed stem, allied to ferns, the horsetails, calamites.
Lepidophyta, plants with scalelike leaves, allied to ferns, the club mosses, lepidodendrons, sigillarias.
**Pteridospermophyta*, the extinct seed ferns.
Cycadophyta, cycads.
Coniferophyta, conifers like the pine and spruce, and the fossil cordaites.
Angiospermophyta, all flowering plants.

Animals

Protozoa, one-celled animals.
  Foraminifera, mostly calcareous, in part arenaceous shelled protozoans.
  Radiolaria, mostly siliceous shelled.
Porifera, the sponges, body wall porous, many with calcareous or siliceous skeleton.
Coelenterata, body cavity serving to carry on all vital functions.
  Hydrozoa, small, body cavity without radial partitions.
    **Stromatoporoidea*, colonial, secreting massive laminated base.
    **Graptolitoidea*, delicate stemlike growths along which the individuals are arranged in series (possibly may belong with bryozoans).
  Anthozoa, the corals, body cavity divided by radial partitions.
Echinoderma, spiny-skinned animals.
  Pelmatozoa, stemmed echinoderms.
    **Cystoidea*, bladder-like form, plates irregularly arranged.
    **Blastoidea*, small, symmetrical, budlike.
    Crinoidea, calyx composed of regularly arranged plates, arms free.
  Asterozoa, starfishes, brittle stars.
  Echinozoa, sea urchins, holothurians.
Vermes, worms, generally unimportant as fossils.
Bryozoa, minute colonial animals that secrete a variety of beautiful and delicate calcareous skeletons.
Brachiopoda, bivalves in which one shell is larger than the other, and, typically, each bilaterally symmetrical.
Mollusca, soft-bodied invertebrates, highly developed.
  Pelecypoda, bivalves in which the two shells are the same in size, and generally symmetrical one to the other.
  Gastropoda, a single cap-shaped or spirally coiled shell, undivided.
  Cephalopoda, straight or spirally coiled shell divided into numerous chambers, or shell solid, internal.
Arthropoda, segmented animals, typically with a pair of jointed appendages to each segment.
  Branchiata, gills developed in connection with the appendages.
    Crustacea, mostly aquatic, with antennae.
      **Trilobita*, primitive marine crustacea with a longitudinally three-lobed shell.
      Ostracoda, small, bivalved crustacea.

Malacostraca, crabs, lobsters.
Arachnida, mostly air breathers, without antennae.
Merostomata, horseshoe crabs, eurypterids.
Euarachnida, scorpions, spiders.
Insecta, insects.
Vertebrata, animals with a notochord or backbone.
Pisces, the fishes.
**Ostracodermi*, primitive fishes with more or less prominent external bony covering, ostracoderms, cyclostomes.
Selachii, sharks.
Osteichthyes, bony fishes.
Dipneusti, lungfishes.
Crossopterygii, fishes having fins with a central fleshy lobe.
Actinopterygii, ray-finned fishes.
Amphibia, cold-blooded animals with limbs and with metamorphosis from water- to air-breathing, salamanders, frogs, etc.
Reptilia, cold-blooded animals, air-breathing.
Cotylosauria, primitive land reptiles.
Squamata, lizards, snakes, and extinct aquatic reptiles.
**Ichthyosauria*, short-necked, aquatic reptiles.
**Sauropterygia*, long-necked, aquatic reptiles.
**Theromorpha*, primitive forms that may include ancestral stock of mammals.
Chelonia, turtles.
Crocodilia, crocodiles, alligators, etc.
**Saurischia*, a great group of lizard-like reptiles, dinosaurs.
**Ornithischia*, another group of dinosaurs.
**Pterosauria*, flying reptiles.
Aves, the birds.
Mammalia, the mammals, warm-blooded, suckle the young.
Prototheria, egg-laying mammals.
Metatheria, young born immature and carried in a pouch.
Eutheria, young well-developed before birth.
Insectivora, insect eaters.
Chiroptera, bats.
Carnivora, flesh eaters.
Rodentia, gnawing mammals.
Edentata, sloths, armadillos.
Artiodactyla, even-toed mammals, sheep, cattle, swine.
Perissodactyla, odd-toed mammals, horses, rhinoceroses.
Proboscidea, elephants.
Sirenia, sea cows, manatees.
Cetacea, whales, dophins.
Primates, mammals with nails, apes, monkeys, man.

SUMMARY

Fossils are the remains or traces of animals or plants preserved in the rocks. Such preservation is commonly dependent on quick burial of the organism in a protecting medium, and on the presence of some sort of hard parts in the organism. The hard parts may be preserved with little or no alteration, or they may be chemically changed without destroying microscopic structure. Replacement of original substances by cal-

cium carbonate is termed calcification; by silica, silicification; by iron pyrite, pyritization. Residual concentration of carbon is termed carbonization. Removal of hard parts by solution leaves an impression in the sediment that is called a mold, and the filling of the cavity enclosed by a mold produces a cast. Fossils may be distorted by pressure.

An index fossil, as commonly defined, is one that has a comparatively small vertical range, a wide geographic distribution, abundance, and distinctive characters that permit definite identification. Such fossils are valuable "markers" of the geologic horizons in which they occur.

Animals and plants are designated scientifically according to a system of binomial nomenclature. There are classificatory divisions of varying degree of comprehensiveness: in ascending order, the chief ones are species, genus, family, order, class, phylum, and kingdom.

CHAPTER XV

LIFE OF EARLY PALEOZOIC TIME

THE AGE OF INVERTEBRATES

The Paleozoic rocks are the oldest that contain abundant evidences of life. Because remains of this life form an essential part of the geologic record, and because the character of the life of these remotely ancient times has much intrinsic interest, we must study the classes of organisms that are represented by fossils in the Early Paleozoic strata. We shall also note the main characteristics of life during the successive periods in the era.

PLANTS OF EARLY PALEOZOIC TIME

That plant life was fairly abundant during the early part of Paleozoic time is a safe presumption because of (1) the prolific fossil remains of animals, all of which are directly or indirectly dependent on plants for food, (2) the appearance of highly organized plant remains in the Devonian and later Paleozoic rocks, and (3) the widespread prevalence of fossils, regarded as calcareous algae. It may be remembered, also, that there are numerous fossil algae in some of the Proterozoic formations. The dark color of some of the Early Paleozoic sedimentary deposits may be due to carbon derived from plants. Bacteria, which are assigned an important role as precipitating agents of calcium carbonate, may have contributed importantly to accumulation of the thousands of feet of calcareous strata which were made in Cambrian, Ordovician, and Silurian time.

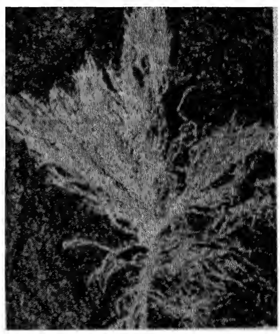


FIG. 93.—A filamentous blue-green alga (*X* 2) from the Burgess Middle Cambrian black shale, British Columbia. (*C. D. Walcott.*)

Marine Plants.—The only certainly known plants from the Early Paleozoic part of earth history are seaweeds (algae). Some of the most interesting of these are the remarkably preserved specimens of gelatinous and membranous algae that appear as shiny black films on bedding planes of a Middle Cambrian shale (Burgess) in British Columbia. No fruiting organs are found and the cellular structure is only rarely shown, so that exact comparison with living algae cannot be made. On the basis of form and mode of growth, C. D. Walcott, who discovered the fossils,

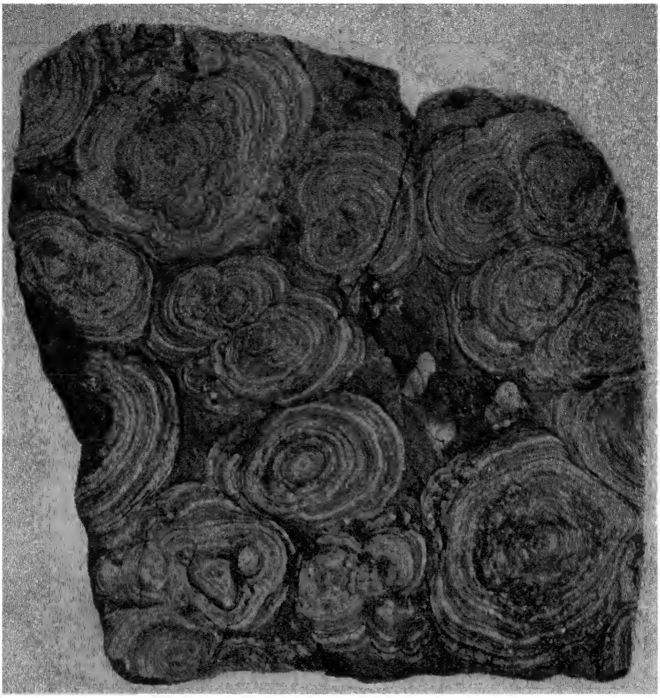


FIG. 94.—Slab of Upper Cambrian (Ozarkian) limestone from Saratoga Springs, N. Y., showing the concentrically laminated growth of the fossil marine alga, *Cryptozoon*. (*Photograph by Walter E. Corbin, Florence, Mass., of specimen in Amherst College Museum.*)

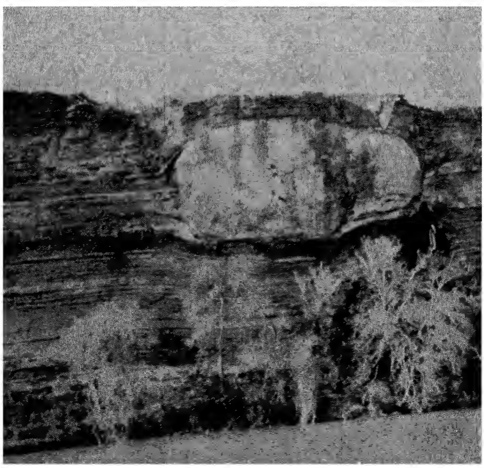


FIG. 95.—A large calcareous algal mass in the Wilberns formation, Upper Cambrian, near Llano, central Texas.

The size of the algal mass may be compared with that of the trees on the river bank. (*A. H. Deen, University of Texas.*)

has distinguished 20 species. Since none of these algae shows a point of attachment, it is assumed that they were floating forms.

Lime-secreting algae (*Cryptozoon*) are especially abundant and characteristic of some of the Ozarkian formations. The algal remains consist of calcareous masses that are varied in size and irregularly rounded in shape. They show a finely laminated concentric structure closely resembling that of some modern blue-green algae. Other types of algae are found in Ordovician and Silurian beds.

Land Plants.—Although no land plants are known before Devonian time, it is probable that the beginning of adaptation to life on the lands occurred very much earlier. This is indicated especially by the high degree of advancement and specialization of the land plants that are encountered in the Devonian. When one remembers the unfavorable situation of land vegetation as regards speedy burial, and all the other factors that make preservation unlikely, it is not surprising that the record of Early Paleozoic land plants is a blank. Moreover, the known deposits of this time are almost wholly marine.

ANIMALS OF EARLY PALEOZOIC TIME

Protozoans

The most primitive and simple animals, the protozoans, consist of a single cell in which are performed all the various function of life, such as assimilation of food, excretion, respiration, reaction to external stimuli, and reproduction. The protozoans are exceedingly varied, but only two classes, (1) Foraminifera and (2) Radiolaria, secrete hard parts that are capable of preservation as fossils. The vast majority of protozoans are aquatic, and almost all of the shelled forms live in the sea. We might suppose that the oldest fossil-bearing beds would be especially characterized by prominence of these simple organisms, but, on the contrary, fossil protozoans are rare in older Paleozoic strata. This may be due partly to conditions unfavorable for preservation of these minute delicate structures, but more probably the scanty fossil records mean that most of the early protozoans lacked hard parts. Excepting a few poorly preserved specimens from Upper Cambrian rocks of England, no fossil Foraminifera were known from Early Paleozoic rocks until recently (1930) when W. L. Moreman reported the discovery of 30 species of sandy-shelled forms from Ordovician and Silurian limestones in Oklahoma. A number of additional kinds have been found subsequently.

Foraminifera are the most important shell-bearing protozoans. Their shell or test, composed of calcium carbonate or sand grains cemented by calcium carbonate, iron oxide, or a complex organic compound known as chitin, is perforated by one or more minute openings (*foramina*). The simplest types consist of a single globular or vaselike chamber with a

rounded aperture, which in some cases is located at the end of a projecting neck. A more advanced type consists of an initial chamber surrounded spirally by a long undivided tube. In still more complex shells there are

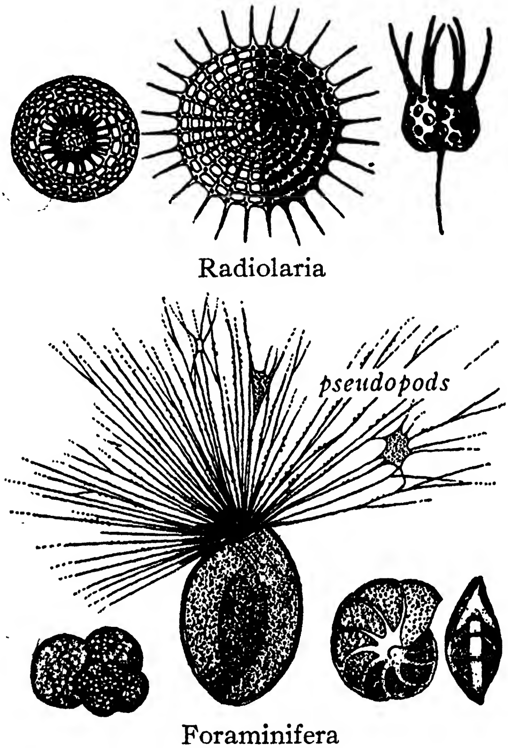


FIG. 96.—Drawings showing typical examples of shell-bearing protozoans. Much enlarged. (*Winifred Goldring, New York State Museum.*)

several chambers arranged spirally, in a straight line, or coil, or in two or more rows.

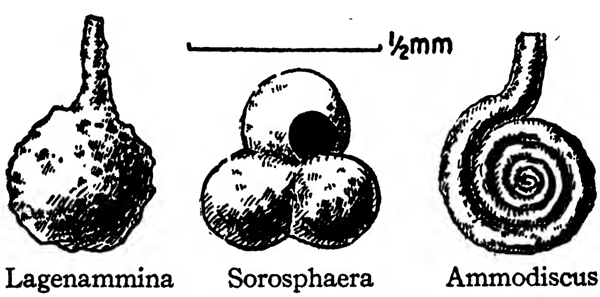


FIG. 97.—Three types of Silurian foraminifera from Oklahoma. (*After W. L. Moreman.*)

Radiolaria secrete a very delicate and beautiful skeleton, in most cases composed of silica. These organisms, whose accumulated remains in the deeper parts of present seas form radiolarian ooze, have been

reported from pre-Cambrian rocks, but they are not definitely identified in Early Paleozoic faunas.

Sponges

Structure and Characteristics of Sponges.—The sponges (Porifera), together with all higher types of animals, are distinguished from protozoans by the fact that the body is composed of many cells which differ in function and are mutually interdependent. Accordingly, animals above the rank of the protozoans are sometimes grouped under the name Metazoa.

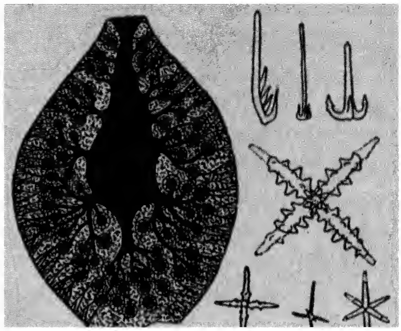


FIG. 98.—Diagrammatic section of a simple sponge showing canal system, central cavity, and vent at the top. At right, a few types of siliceous sponge spicules, much enlarged. (*Winifred Goldring, New York State Museum.*)

In simplest form, the sponge is a hollow, globular or cylindrical structure with a large opening at the top. The body walls are pierced by numerous small openings. These passageways are lined by cells provided with mobile, hairlike appendages which by a

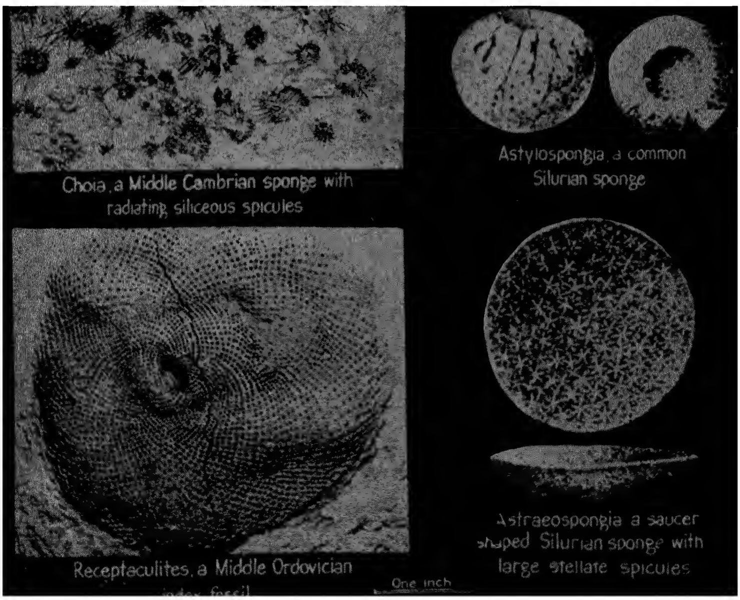


FIG. 99. Some types of Early Paleozoic fossil sponges.

rhythmic motion produce gentle water currents toward the interior cavity of the animal, and thence outward by the large vent at the top. There is wide variation in the shape and size of different species of sponges and,

through development of buds and branches, there may be much difference in the form of individuals of the same species. The sponges are aquatic creatures, mostly marine. Some of them have no hard parts and are therefore not capable of fossilization. Two classes, however, one with a siliceous, the other with a calcareous, skeleton occur as fossils. In some of these sponges the hard parts consist of small, unconnected elements (*spicules*) which are embedded in the walls, and when the animal dies these are released by decay of the soft tissues. The form of the animal as a whole is lost. In others, the spicules are knit together so as to preserve the general form of the sponge or colony of sponges, and these are naturally much more interesting and important fossils.

Early Paleozoic Sponges.—Among Cambrian fossils the siliceous sponges are well represented by several types, including many with a delicate netlike skeleton that resembles the modern glass sponge known as Venus' flower basket.

Sponges were common in Ordovician times and many of them are valuable index fossils. One of the most important types, which, however, may possibly represent an entirely distinct class of organisms, is called *Receptaculites*. This has regularly arranged chamberlets, which in the basal portion suggest the large center of a sunflower. It is a characteristic fossil of some of the mid-Ordovician (Trenton) formations.

The Silurian rocks contain a somewhat similar genus (*Ischadites*), and in addition there are large numbers of apple-shaped (*Astylospongia*) and saucer-like (*Astraeospongia*) siliceous sponges in some beds. At certain places in Tennessee, sponges weather out of the rocks in greatest profusion and may be gathered by the bushel.

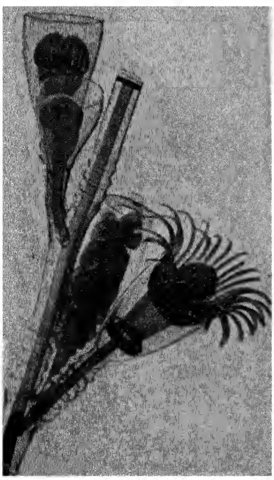


FIG. 100.—A modern hydrozoan (Obelia). Much enlarged. (*American Museum of Natural History.*)

Hydrozoans

General Character.—Hydrozoans are aquatic, mostly marine animals of small size, somewhat more highly organized than the sponges. They are commonly colonial and some of them build a considerable skeletal deposit of calcium carbonate. The individual animal (polyp) consists of a cylindrical tube composed of two cell layers. It is attached at its base and bears at the free end a ring of tentacles surrounding the so-called mouth, which serves also as vent for the discharge of waste from the primitive digestive cavity. This cavity comprises the entire space enclosed by the body walls, a feature that, including the corals, distinguishes the phylum Coelenterata. The hydrozoan colony grows by asexual budding of new polyps, forming a delicate branching frond, or, where the buds arise from a basal expansion, a mosslike felt. In many

cases, the latter secretes a dense calcareous deposit at the base (hydrocorallines, stromatoporoids).

Some of the hydrozoan buds in each colony are very different from those that have been described, for they develop into umbrella-like jellyfish or medusae that break away and are free-swimming. The medusae reproduce sexually, forming the vegetative, attached polyps or other medusae. There is thus an alternation of generation. Medusae are not adapted for fossilization since they have no hard parts, but under exceptional conditions, as in the Middle Cambrian Burgess shale of British Columbia, clearly identifiable impressions of these delicate organisms have been discovered.

Stromatoporoids deposit large masses of calcium carbonate in successive thin layers separated by low rods or pillars. Distinctive surface

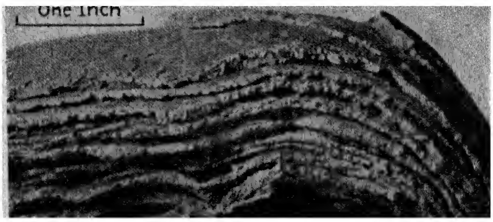


FIG. 101.—A stromatoporoid (*Stromatocerium*) from Ordovician rocks of Tennessee. (*R. S. Bassler, Tennessee Geol Survey.*)

features, such as hummocky elevations with a large central pore and radiating grooves, may be present.

Stromatoporoids flourished during parts of Paleozoic time when they were of importance as rock builders. The principal representatives of this class in the Ordovician period are columnar growths with external fluting (*Beatricea*), rounded, hemispherical growths (*Stromatocerium*), and flat expanding forms (*Labechia*). The Silurian species are mainly large irregularly laminated masses in which the vertical pillars extend only between the layers, rather than continuously across several layers (*Clathrodictyon* type). There are 17 described stromatoporoid species in the Ordovician of America, about 70 in the Silurian, and a still larger number in the Devonian.

Graptolites.—A very interesting group of fossils, known only from the Paleozoic rocks and almost entirely restricted to the Ordovician and Silurian, is the graptolites.[1] These are colonial growths in which the rows of tiny cups that housed the polyps were composed of resistant but flexible chitin. The fossils appear almost exclusively as flattened carbonaceous films on the bedding planes of black shales. Graptolite remains are extraordinarily abundant in some of these shales, while other kinds of organisms are often very scanty. Occasionally they occur in limestone. Accurate correlation of graptolite-bearing deposits, even on

[1] According to Ruedemann and Ulrich, it is possible that the graptolites are really a branch of the bryozoans.

opposite sides of the earth, as in England, United States, and Australia, is possible (1) because the animals, attached to seaweeds or supported by a float of their own construction, were transported widely by oceanic currents, and (2) because there was comparatively rapid evolution of different species so that beds only a few feet apart vertically may be characterized by entirely different graptolite assemblages.

Most graptolite colonies are straight, simple or branching stems with the small polypary cups (*hydrothecae*) on one or both sides, more or less overlapping and resembling the teeth of a saw. Some colonies have a leaflike form, and a few are spirally coiled. The polyps grow by succes-

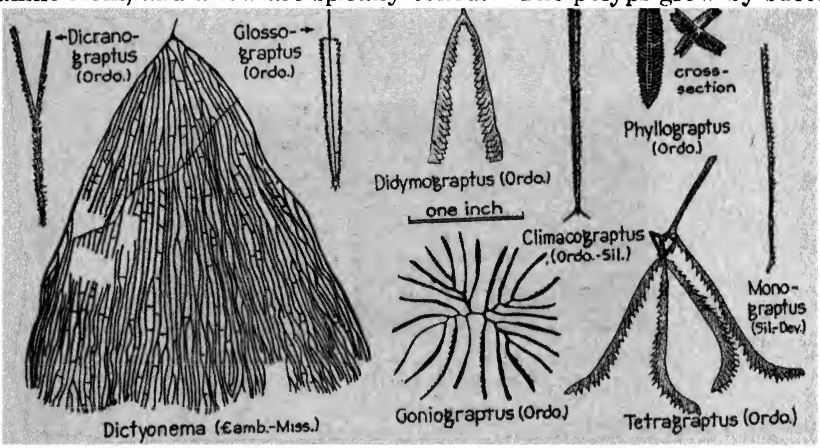


FIG. 102.—Some representative types of graptolites. (*Winifred Goldring, from Ruedemann, New York State Museum.*)

sive budding from the first formed cup. In the more highly developed graptolites the rows of cups were supported by a slender solid axis.

Evolutionary changes among the graptolites are seen (1) in the form of the colonies, and (2) the shape and arrangement of the cups. The lower, and therefore older, graptolite zones show species in which numerous branchings are characteristic, while successively appearing later types have branches reduced to 16, 8, 4, 2, and finally 1. Primitively, also, the branches appear to have hung more or less directly downward, but in later, more advanced genera they grew horizontally outward, and, finally, turning upward, the rows of cups were established in a position back to back. There is, therefore, a tendency in colony form to pass from many branches to a single one and from downward-hanging branches, each with a single row of hydrothecal cups, to those with a double row of cups growing back to back. The simplest hydrothecae are short cylindrical tubes growing obliquely outward from the initial cup. In specialized types these turn at right angles to the stem or even form an S-shaped bend, and part of the tube may be variously constricted.

The graptolites first appear in the Middle Cambrian (Burgess shale) and are widespread in the uppermost Cambrian rocks (*Dictyonema* beds). The Ordovician marks the heyday of graptolite abundance and differentiation, and in the shale deposits where they occur they are much the most important among all the fossils. There are 40 genera and more than 230 species of graptolites in the Ordovician rocks of North America. By Silurian time they had greatly declined in numbers but are still important. Here occur some of the most peculiar and highly specialized examples. In America, about 23 genera and 100 species of Silurian graptolites are recorded. A few stragglers consisting of the most long-lived, primitive stocks lived on into the Devonian and early part of Mississippian time.

Corals

General Character.—Corals are bottom-dwelling marine coelenterates. They are varied in color and, as their scientific name (Anthozoa—

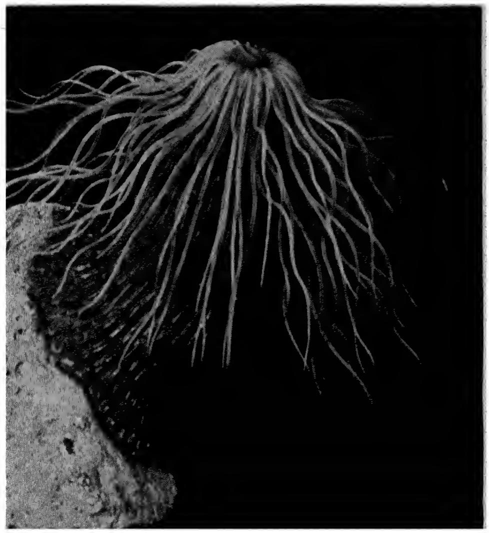


Fig. 103.—Model of a sea anemone.

This animal is closely related to the corals but does not have hard parts. (*American Museum of Natural History.*)

flower animals) suggests, beautifully flower-like in form. Some are solitary individuals, but the majority grow in colonies that in many cases are several feet across. Only a few of these creatures are lacking in hard parts, most of them secreting a calcareous or horny skeleton. The calcareous species are abundantly represented by fossils and they have been very important at certain times and places as rock builders. Many of the corals are good index fossils. If the ancient coral polyps were affected by temperature conditions like the modern, the common occurrence of fossil corals in a geologic formation may be interpreted to signify that the deposit was laid down in moderately warm waters. Corals are mostly inhabitants of the very shallow parts of the sea.

Structurally, the body of the coral polyp differs from that of the hydrozoan in the presence of numerous radial walls of membrane (*mesenteries*), some of which project inward only a short distance from the circumference of the body, others reaching and joining a slitlike gullet that extends part way downward from the mouth. Except in a few cases, the calcium carbonate skeleton is secreted by the outer portion of the body wall, which thus encases the lower part of the coral in a cylindrical or conical tube or in some cases forms a flattish basal expansion. The soft body wall is commonly infolded strongly between the mesenteries so that radial partitions (*septa*) of calcium carbonate are built up. The upper edges of the septa generally slope inward from the outer calcareous wall (*theca*), forming a central depression (*calyx*). In Mesozoic and Recent corals, there are typically six primary, prominent septa, but, in the Paleozoic, those having septa show a fourfold symmetry. Among the latter, one or more of the four main septa may be repressed, forming a depression or furrow (*fossula*) in the calyx. At successive stages in the life of the coral polyp, it may draw upward slightly and deposit a new basal platform (*tabula*) across the tube, and vacated spaces between the septa may be partitioned off by small oblique plates (*dissepiments*). In some cases a rodlike axis is secreted in the center of the calyx (*columella*). These and other structures give complexity and wide variation to the hard parts of different species of corals, which makes them the more useful as markers of strata that contain them. One important group of Paleozoic corals (*Tabulata*) is characterized by the vestigial nature of the septa, abundant development of tabulae, and the generally small size of the individuals that always grew in colonies. The "honeycomb" and "chain" corals belong to this group.

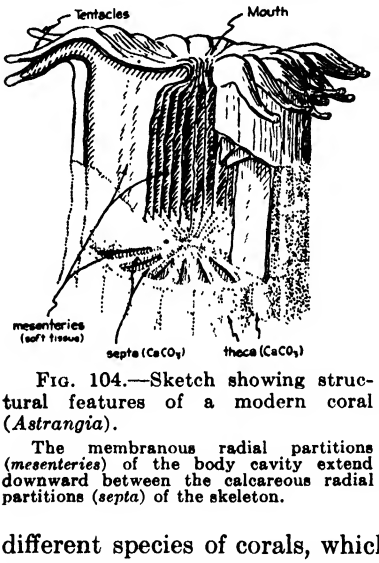


FIG. 104.—Sketch showing structural features of a modern coral (*Astrangia*).

The membranous radial partitions (*mesenteries*) of the body cavity extend downward between the calcareous radial partitions (*septa*) of the skeleton.

Occurrence of Corals in Early Paleozoic Rocks.—Corals are not a dominant element in the faunas of Early Paleozoic time, but in each of the periods included here there were a few common and widespread species that are characteristic of the deposits containing them.

The Lower Cambrian, in both North America and the Old World, has yielded many specimens of what are probably very primitive corals or possibly sponges. These are the archeocyathids, subcylindrical or conical in shape, and attaining a maximum length of nearly a foot. They are specially distinguished by the thick, porous nature of the outer and radial walls, and the presence of a sort of plate that unites the top of the septa, flooring the calyx. Locally, the archeocyathids make reefs (or bioherms)

50 feet or more in thickness. A limestone in Australia, some 200 feet thick and extending horizontally for 400 miles, is largely composed of them. The presence of archeocyathids in Labrador, islands in the Arctic north of Siberia, and in Antarctica suggests that the high latitudes were at least not frigid at this time.

For some reason, corals are rare or lacking in the Middle and Upper Cambrian, but they appear at various horizons in the Ordovician. Characteristic genera are the

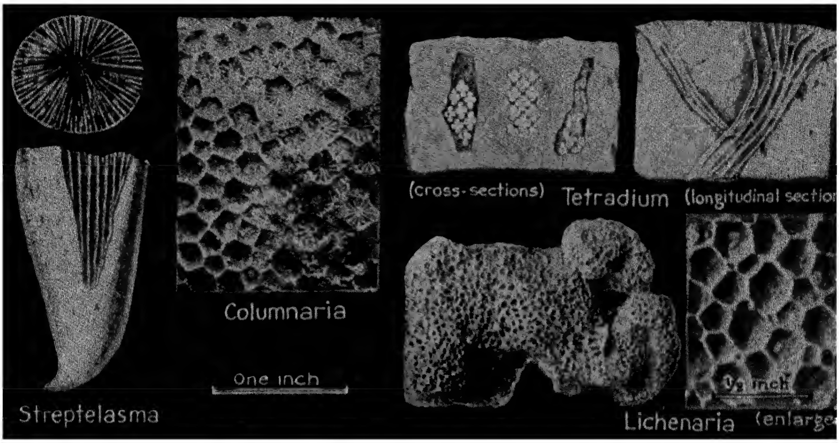


FIG. 105.—Some representative types of Ordovician corals.

colonial corals, *Tetradium* and *Columnaria*, and the horn coral, *Streptelasma*. The chain coral (*Halysites*), though typically a Silurian fossil, has been found to be represented by some species as old as mid-Ordovician. Altogether, some 15 genera and 30 species of Ordovician corals have been described.

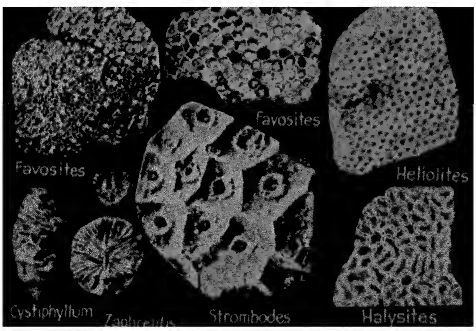


FIG. 106. Some representative types of Silurian corals. (One-half natural size.)

The first really abundant development of corals occurred in Medial Silurian time, when at many places in North America they made reef limestones. The number of American genera increased to 67 and that of species to 373 or more. At certain places, notably in Wisconsin, Iowa, and Indiana, well-exposed sections of the ancient reefs (bioherms) may be studied, and large collections of coral species may be made. There are colonial corals of many types, a few with large individual polyps (as *Strombodes*),

but the majority with units of small size (*Favosites*, *Thecia*, *Alveolites*, *Cladopora*, *Halysites*, *Heliolites*). Especially interesting are the chain coral and the honeycomb. Horn corals of various sorts are not uncommon (*Zaphrentis*, *Streptelasma*, *Cystiphyllum*). A strange coral (*Goniophyllum*), shaped like a four-sided pyramid and provided with a cover composed of four close-fitting plates, is a characteristic fossil in the Silurian of northern Europe, and more rarely in North America.

Echinoderms

General Character.—The echinoderms (*spiny skin*) comprise a host of marine animals that are highly varied in appearance and size, but nearly all characterized by radial symmetry and by the presence of a skeleton consisting of calcareous plates or bodies embedded in the skin. Most familiar to visitors at the seashore are the starfish and sea urchin which crawl about on the shallow sea bottom. Less generally known, but during Paleozoic time far more important than these mobile forms, is a group of sedentary or attached echinoderms that includes the crinoids, which are represented by living species, and the cystoids and blastoids, both of which are confined to the Paleozoic. The free-moving echinoderms have the mouth on the under or ventral side, but the attached forms are inverted, the mouth and ventral side being uppermost. The dorsal side is underneath and bears a stalk by which the animal is fastened. The echinoderms are much more highly organized than the coelenterates, for they have a true digestive canal, a distinct body cavity, a vascular and water circulatory system, a more highly developed nervous system, complex skeletal and structural elements, and an exclusively sexual mode of reproduction.

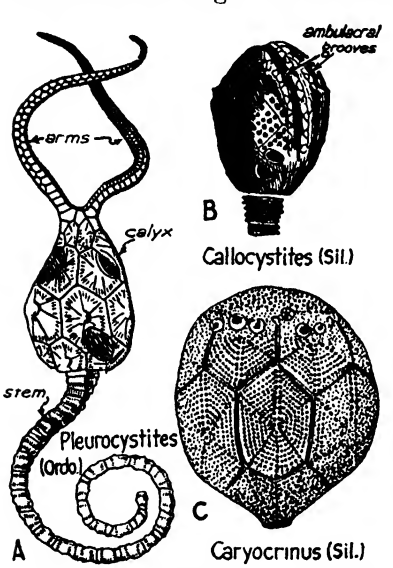


FIG. 107.—Early Paleozoic cystoids. (*A*) A form with free arms and with stem attached. (*B*) A type with structures corresponding to arms borne on the calyx. (*C*) A symmetrical, ornamented form that is common in some Silurian beds. (*Winifred Goldring, New York State Museum.*)

Cystoids.—The most primitive and oldest known echinoderms are the cystoids. These have a skeleton of irregularly arranged plates joined rigidly together to form a saclike calyx, an inch or two in average diameter. The calyx was attached to the sea bottom or some foreign object by a short stem, or in some cases it was affixed directly. Like other sedentary echinoderms, the cystoids fed on microscopic organic matter in the sea water, which was carried to the mouth along canals (*ambulacral grooves*) on the upper surface of the calyx or on the arms.

Some species had two or more rather simple arms, and a majority show peculiar perforated structures in the plates.

The cystoids appeared first in the Cambrian and attained maximum numbers and variety in the Ordovician (21 genera, 59 species) and Silurian (28 genera, 113 species). Only a very few cystoids are known from beds younger than Silurian. They are therefore characteristic of the older Paleozoic strata.

Blastoids.—A second group of the stemmed echinoderms is known as the blastoids. These have a symmetrical, budlike calyx, composed of 13 plates, and they have five ambulacral or food groove areas that extend downward from the summit along the sides. They are about a half inch in average diameter. In unusually well-preserved specimens, a multitude of threadlike armlets is found arising from the borders of the ambulacra and entirely concealing them. Inside the calyx, beneath the ambulacra, are bundles of flattened tubes that probably functioned as respiratory organs (see Fig. 196).

The first known blastoids, occurring in Ordovician strata, show certain characters suggesting transition from an ancestral cystoid stock. This group is not common either in the Ordovician (one genus, one species) or Silurian (one genus, three species), but it reached a sudden and rather remarkable climax in the Mississippian period.

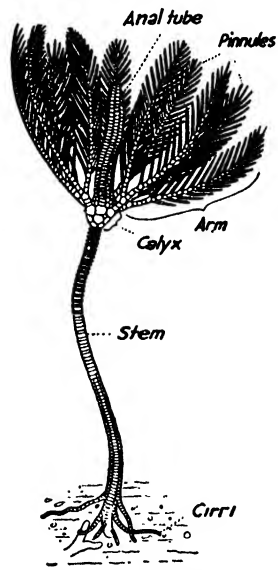


FIG. 108.—Diagram of a simple crinoid showing structural features. (*After Bather.*)

Crinoids.—Much the most important class of Paleozoic echinoderms includes the crinoids. These are usually long-stalked creatures with a calyx composed of regularly arranged plates and provided with well-developed movable arms.

The *stem* or stalk consists of very numerous superimposed button-like disks, each with a rounded or five-angled opening through the center. The stem may carry lateral appendages (*cirri*) at intervals, and the lower end is anchored by rootlike branches, by a bulbous or heavy discoid terminal growth, or in some cases by coiling around a seaweed or other foreign object. The length of the stem is ordinarily not greater than 1 or 2 feet but some Jurassic specimens show more than 20 feet of stem, the end not being observed.

The *calyx* is cup-shaped or globular and encloses the more important organs of the animal. The lower (dorsal) portion, below the arms, is characterized by regularly disposed plates, the shape and arrangement of which are constant in each species. The primary symmetry is always pentameral (fivefold) but in very many crinoids the introduction of an

additional plate or series of plates (*anals*) on one side of the calyx introduces a bilateral symmetry. The crinoids are classified mainly on the basis of the plate arrangements of the calyx, and consequently this is the most important part of the fossil for study. If the plates become separated after death of the animal, or if stem or arm pieces only are found, it is not possible ordinarily to identify the species to which these parts belonged. The upper (ventral) part of the calyx is generally formed of numerous irregularly arranged plates. The mouth is centrally located and externally visible in some forms but concealed beneath the ventral covering in others. The anal vent is also located on the upper surface of the calyx, sometimes at the end of an elevated tube or proboscis.

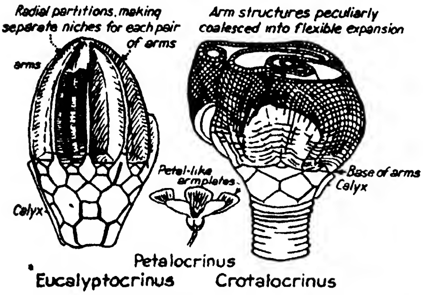


FIG. 109.—Some peculiarly specialized crinoids that occur in Silurian formations of the Mississippi Valley region of North America and the Baltic region of Europe.

The *arms* of the crinoid are movable columns of small channeled plates arranged in single or double alternating series. The furrow along the arms, covered by small plates, carries water, with its contained microscopic food matter, to the mouth. Among all of the more highly organized crinoids, each plate segment of the arms carries a small branchlet (*pinnule*) similar to the arm in structure and function. Various numbers of arms and types of branching are observed but the arrangement of arms in all species shows a basic five-fold symmetry.

Living crinoids are highly gregarious and inhabit mainly the shallow, clear, moderately warm portions of the sea. A majority of the fossil forms doubtless were similar in habits, as indicated by the enormous quantity of their remains in some of the Paleozoic formations, and by their association with reef corals and other shallow-water invertebrates.

Early Paleozoic Crinoids.—Crinoids are not certainly known from Cambrian rocks but they are fairly well represented in the Ordovician system (34 genera, 110 species). Several of these ancient forms are rather specialized, well-advanced types that are good index fossils. Each of the main orders of crinoids, except the articulates, to which most modern crinoids belong, is present in the Ordovician faunas. Silurian time witnessed a considerable advance in the number and variety of crinoids (in America 69 genera, 293 species), and some of the species were very peculiarly specialized. In one (*Eucalyptocrinus*), the arms fitted into partitioned spaces formed by solid calcareous walls raised above the calyx; in another (*Crotalocrinus*), the arms joined laterally to form a broad flexible network; and in still another (*Petalocrinus*), the arm structures were developed into solid petal-like projections extending outward from the tiny calyx. All of these types occur in the Silurian of the central United States and of northern Europe. In some of the Silurian deposits there are numerous specimens of minute crinoids (*Stephanocrinus*, *Pisocrinus*) with calices no larger than a pea.

The structural characters that are of chief importance in classification and in the evolution of the crinoids are (1) the plan of the plates in the dorsal part of the calyx, and (2) the number, method of branching, and structure of the arms.

Starfishes and Echinoids.—Starfishes are known as fossils in the older Paleozoic rocks. While their presence and comparatively high degree of development are interesting, this group of echinoderms is not important in any of the fossil faunas. The echinoids or sea urchins were represented in the Ordovician by a single genus with small globular shell (*Bothriocidaris*) and in the Silurian by four known genera. The ancient echinoids are characterized chiefly by the large number of columns of plates in the shell. The time of great abundance and differentiation of the echinoids was in the Mesozoic, to which chapter we may reserve more detailed consideration.

Worms

Generally speaking, no class of animals is less adapted to preservation in the fossil state than the worms, whose bodies are as a rule lacking in hard parts. This is unfortunate, for the extreme variety of modern forms and the abundance of species dwelling in the sea suggest that the paleontologic record would be much richer if worms were well represented. Fossils in this group include (1) pincer-like or variously shaped, tooth-bearing jaw parts (termed *scolecodonts*) of annelid worms, (2) a few types that secrete for themselves calcareous tubes which are generally attached to some shell or other foreign substance, and (3) the borings or trails that are made in sediments on the sea floor.

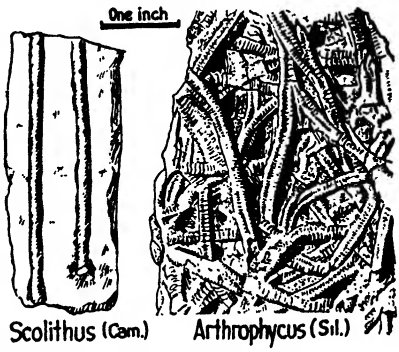


Fig. 110.—Fossil worm trails from Early Paleozoic rocks.

Scolecodonts are surprisingly abundant fossils in some of the Ordovician and Silurian strata, and the fact that the various kinds discovered at different horizons are readily distinguishable makes this group of fossils useful as stratigraphic markers. Most of the specimens are less than 1 mm. in length. Fossil worm tubes are known from Ordovician and Silurian rocks, and each of the Early Paleozoic systems carries in places the trails and borings of worms. Certain zones in the Cambrian are specially characterized by an abundance of vertical borings (*Scolithus*) of rather small diameter that generally occur in sandstone. In some cases these borings are filled by soft material that is removed readily, but the fillings may also be harder than the matrix and weather in relief. One of the guide fossils in the Medinan sandstones of the Appalachian region is *Arthrophycus*, which at first was thought to be the cast of a seaweed but is now interpreted as the trails of marine worms.

One remarkable exception to the rule concerning preservation of these soft-bodied creatures is found in a large collection of fossils from the Burgess shale, of Medial Cambrian age, in British Columbia. Among other fossils is a profusion of worms, flattened by pressure but showing body segments, legs, delicate hairlike appendages,

and even internal structures. This amazing glimpse of a highly developed assemblage of soft-bodied marine organisms serves to emphasize the conclusion that a host of similar animals, including the worms, existed in Early Paleozoic time but has left no fossil record.

Bryozoans

General Character.—Few classes of marine invertebrates have a record of highly varied and long-sustained evolution that exceeds that of the bryozoans, yet, because of the minute size of the individuals and of many of the colonies, their importance is easily overlooked. With exception of a single genus, they are exclusively colonial animals that secrete a calcareous, horny, or membranous covering that in different species exhibits a multitudinous variety of form and structure. Of course, only the calcareous forms are adapted for preservation as fossils. The most primitive bryozoans build a simple, chainlike series of tubes, one budding from another. By branching and lateral confluence of tubes, the more complex types of colonial structures are produced. Some grow in slender, plantlike tufts; some spread over shells or other foreign objects in a delicate network of interwoven threads; or they form thin, leaflike expansions, rounded branches, lacy fronds, or massive subglobular or hemispherical bodies. There are several thousand described fossil species, ranging in age from Ordovician to Recent, and during parts of geologic time the bryozoans were important rock builders.

FIG. 111.—A colony of modern bryozoans (*Bugula*), much enlarged. (*American Museum of Natural History.*)

Superficially, the bryozoans resemble certain hydrozoans, but they differ from them radically in the possession of a distinct body cavity, an alimentary canal, a highly developed nervous system, and delicate respiratory tentacles surrounding the mouth. The colonial skeleton (*zoarium*) has various structural peculiarities which with the almost microscopic size of the individual habitations (*zooecia*) make it easy in most cases to distinguish the bryozoans from other organisms. Identification of species often requires the making of thin sections in order to determine internal structure, but this is not without advantage, since it

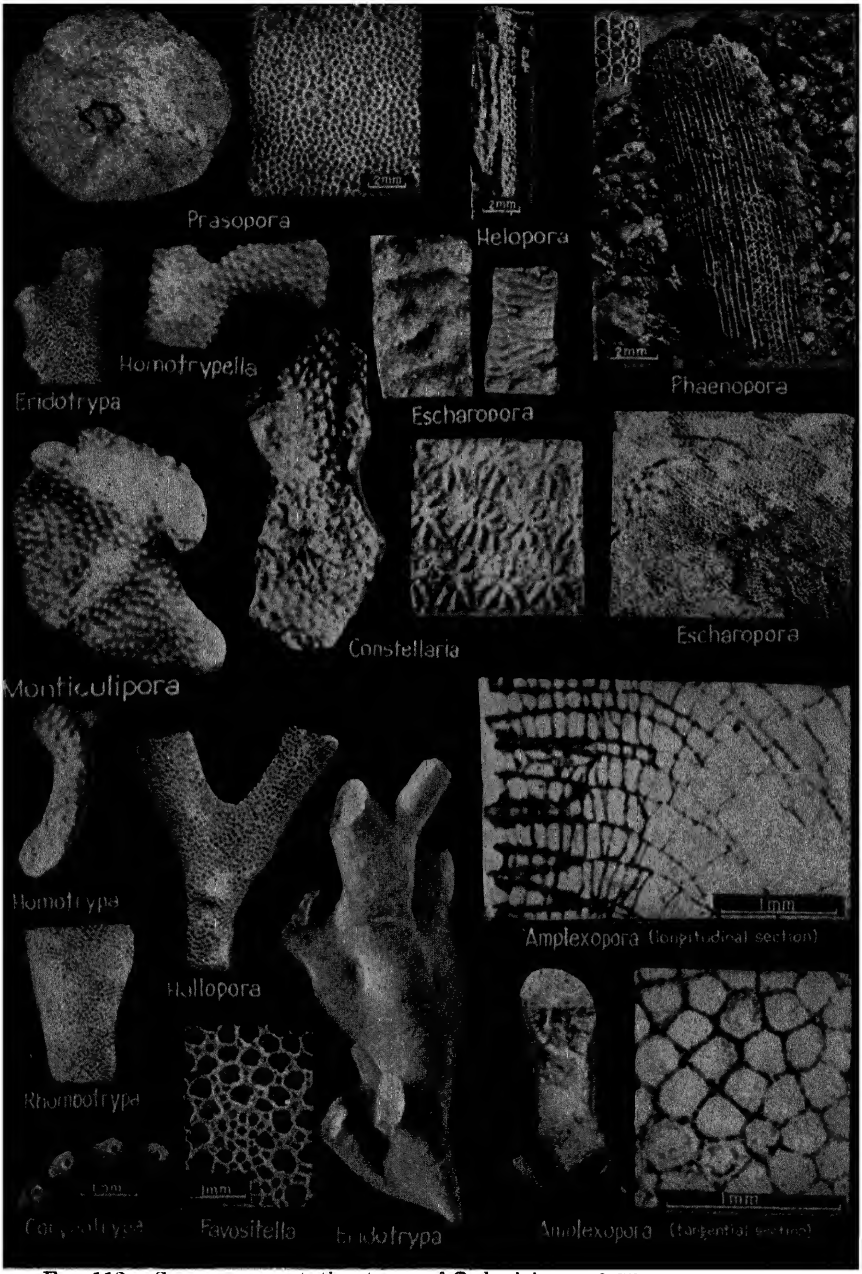


Fig. 112.—Some representative types of Ordovician and Silurian bryozoans.

is possible in many cases to recognize a species embedded in hard rock, even though surface characters are not shown. Many of the bryozoans were widely distributed geographically but short-ranging vertically; they are therefore good index fossils of the formations in which they occur.

Features that are most important in the evolution and classification of the bryozoans are (1) characters of the zooecial apertures, (2) internal structures, and (3) the mode of colonial growth, which determines the form of the zoarium.

FIG. 113.—Ordovician shale rich in delicate ribbon-like and lacelike fossil bryozoans from the Baltic region of Europe. (*R. S. Bassler, U. S. National Museum.*)

Early Paleozoic Bryozoans.—The oldest known bryozoans occur in Lower Ordovician limestones (unless graptolites should be proved to belong in the bryozoans). In some of the Middle and Upper Ordovician deposits, especially certain limy shales, they became extraordinarily abundant, in both individuals and species. America has yielded at least 74 genera and 392 species of Ordovician bryozoans. As compared with later bryozoan faunas, those of this time are characterized by the preponderance of massive colonial growths ("stony bryozoans"). This was the time of maximum development of the so-called trepostome bryozoans which are characterized by long zooecial tubes with numerous cross partitions or diaphragms.

Some of the Silurian formations, especially those belonging to the lower and middle parts of the system, contain very abundant bryozoans, but the large massive types are less common. There are numerous delicate branching colonies and the first important development of lacelike fronds. The American Silurian bryozoans number some 95 genera and 336 species.

Brachiopods

General Character.—Brachiopods are marine shelled animals that are possibly related to the bryozoans and accordingly are sometimes

united with them under the name Molluscoidea. It seems preferable, however, to regard each as a distinct phylum, since the external form, average size, and complete absence of colonial development in the brachiopods do not remotely suggest any of the bryozoans.

Brachiopods have two unequal shells or valves, each of which is bilaterally symmetrical. They consist of calcium carbonate in the great majority of species, but some have chitinous shells, impregnated with calcium phosphate and carbonate. The form of the shell is variable. Generally both valves are convex, but they may be nearly flat; one or other of the valves may be convex while the opposite is concave: or one

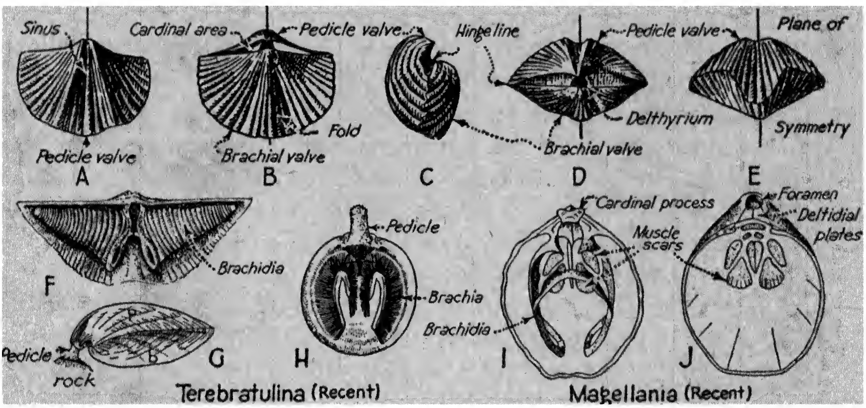


FIG. 114.—Drawings showing the form and structural features of brachiopods. *A* to *E* are views of a single fossil shell from different directions. Note that the two halves of each valve are symmetrical (*A*, *B*, *D*, *E*) but that one valve is not symmetrical to the other. *F* shows the spiral internal supports for the brachia in *Spirifer*. *G* to *J* from living species. (*F to J after Winifred Goldring, New York State Museum.*)

valve may be cone-shaped, the other fitting like a lid upon it. In most cases the posterior portion of the shell, where the valves are hinged or held closely together, is pointed in a beak. One of the valves is designated as pedicle or ventral and the other as brachial or dorsal. During all or part of the existence of the brachiopod after the free-swimming larva settles down, the shell is attached to the sea bottom by a fleshy stalk (*pedicle*) that projects posteriorly between the valves or through an opening in the pedicle valve which generally is dorsal in position. With increasing age, the pedicle opening may become closed and the pedicle itself atrophied. Some brachiopods are anchored by projecting spines or are cemented to foreign objects by the whole or part of the surface of the ventral valve.

Some brachiopods are smooth, except perhaps for faint concentric markings that indicate interrupted growth. The greater number develop radiating striae, ribs, or plications that ornament and may strengthen the shell materially. The median portion and front margin of one valve

are frequently depressed (*sinus*), while the corresponding part of the opposite valve is elevated (*fold*). Spines may be developed in various parts or over the entire surface. Between the beak and the hinge line in many species a flattened or curved triangular space (*cardinal area*) is observed. It is more highly developed in the pedicle valve and is bisected by a small triangular opening (*delthyrium*) for the pedicle. The opening may be partially closed by a plate (*deltidium*) secreted by the pedicle, or by a pair of plates (*deltidial plates*) secreted by an extension of the mantle that builds the pedicle valve. The shells of most living species are light-colored and unornamented, but some bear vivid color markings. It is interesting to find at least some fossil brachiopods in which traces of color patterns are preserved. The large, externally sculptured brachiopods of Paleozoic time must have been objects of much beauty if adorned by brilliant coloring.

The more primitive brachiopods have no definite hinge structure, the valves being held together merely by muscles. More advanced shells have hinge teeth on the pedicle valve that fit into sockets on the brachial valve, and the hinge line may be considerably extended laterally. The valves are pulled together by muscles attached to the interior and are opened by other muscles extending from the floor of the pedicle valve to the end of a lever-like projection (*cardinal process*), near the beak of the brachial valve, that passes between and beyond the hinge teeth. These structures may be supplemented and supported by plates of various shape and position inside the shell. Finally, in all advanced types of brachiopods, the delicate fleshy arms (*brachia*) that serve to propel food particles toward the mouth are supported by calcified projections attached near the beak of the brachial valve. These may consist of moderately short, curved processes (*crura*), of a loop, or of two thin, spirally coiled ribbons.

The evolution of the brachiopods along various lines is shown by (1) composition and structure of the shell, (2) articulation of the valves, (3) nature of the pedicle opening and method of attachment, (4) form and surface ornamentation of the shell, and (5) development of various internal structures.

Early Paleozoic Brachiopods.—Brachiopods are particularly characteristic of Paleozoic rocks, for they were most abundant and varied during this era, while in the Mesozoic and Cenozoic time they were represented by only a few surviving stocks of rather simple type. More than 3,500 species are already known from Paleozoic rocks of North America.

Cambrian.—The Cambrian brachiopods are generally small, mostly less than a half inch in length and width. The simplest, most primitive shells predominate, for the unhinged shells composed partly or wholly of lime phosphate are much more numerous than those with hinged, calcareous valves. Some of these shells had nearly equal valves with a large opening for the pedicle shared by both valves, a feature that is repeated in the very earliest stages of later brachiopods.

Characteristic Cambrian genera are "*Obolus*" (*Parobolus*), *Lingulella*, and numerous others in the family Obolidae, with rounded or pointed thin shells bearing a grooved cardinal area; *Obolella*, *Acrothele*, and *Acrotreta*, more or less strongly conical shells subcircular in outline, with the apex of one valve open for passage of the pedicle; and *Billingsella*, *Eoorthis*, and other primitive genera that mark the beginning of the calcareous-shelled, hinged brachiopods. Walcott lists 59 genera and 536 species in his monograph on the Cambrian brachiopoda of the world, of which 45 genera and 346 species occur in North America.

Ordovician.—All of the four brachiopod classes are represented in the Ordovician rocks. A marked advancement over Cambrian species as shown by (1) dominance of hinged calcareous over unhinged phosphatic shells, (2) increase in average size, variety, and numbers, (3) prevalence of strongly striated or plicated shells, (4) development of interlocking anterior margins, with fold and sinus, (5) abundance of concavoconvex shells, and (6) the appearance of specialized internal structures such as spiral supports

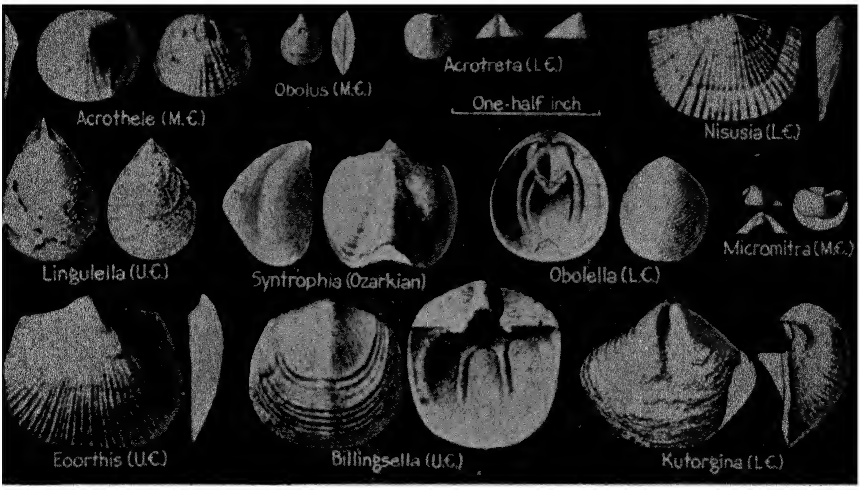


FIG. 115. Some representative types of Cambrian brachiopods.

for the brachia. Several important groups which are well represented throughout most of later Paleozoic time make their appearance.

The family called Orthidae is especially characteristic and at the peak of its evolution. The shells are generally wide-hinged and strongly plicated. They exhibit an evolution in form from *Orthis*, with pedicle valve strongly convex, brachial flat, to *Plectorthis* and *Platystrophia*, with valves subequally convex, and to *Hebertella*, with pedicle valve flattened and the brachial strongly convex. *Dalmanella*, with a strongly punctate shell, is also common. Another very important family is the Strophomenidae, in which the shells are generally wide-hinged and flat or concavo-convex. The most common genera are *Rafinesquina*, *Leptaena*, and *Sowerbyella*, with convex pedicle valve, and *Strophomena*, with convex brachial valve. *Leptaena*, which is distinguished by strong transverse crenulations and a sharply bent marginal area, is one of the very long-lived brachiopod types, persisting practically unchanged from Ordovician to Mississippian time. The rhynchonellid group, distinguished generally by strongly plicated shells with pointed beaks and no cardinal area, is represented especially by *Rhynchotrema*, which is very abundant and widespread in some formations. The earliest spire-bearing brachiopods are the Ordovician *Zygospira*, *Catazyga*,

and *Cyclospira,* individuals of which are common in places, but the number of species is not large. *Atrypa,* which has a different type of spire, appeared in Late Ordovician time; it became exceedingly abundant in parts of the Silurian and Devonian. The number of described Ordovician brachiopods in America is about 65 genera and 472 species.

Silurian.—The Silurian brachiopod fauna continues most of the main lines of development seen in the Ordovician. The total number of species is still larger and some beds are practically made up of brachiopod shells.

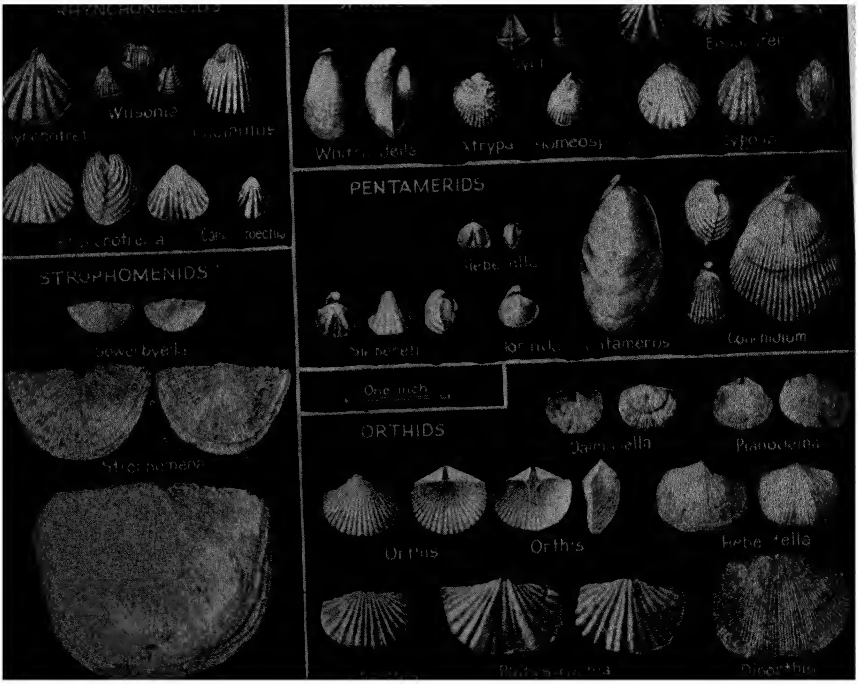


FIG. 116.—Some representative types of Ordovician and Silurian brachiopods.

Most of the orthid genera persist in the Silurian, *Dalmanella* being especially important. Among strophomenids are *Leptaena, Sowerbyella,* and the notched-hinge-line genera *Stropheodonta,* with convex pedicle valve, and *Strophonella,* with convex brachial valve. Rhynchonellids are represented by a number of genera, among which may be mentioned *Rhynchotreta* and *Camarotoechia.* A family that includes several important Silurian index fossils is the Pentameridae. These are mostly smooth, but there are some plicated shells in which the interior is divided near the beaks by prominent converging partitions. The most important genera are *Pentamerus, Stricklandinia, Conchidium,* and *Gypidula.* The spire-bearing brachiopods show a large increase in importance and there are several distinct types of spires. *Atrypa, Eospirifer, Cyrtia, Cyrtina, Homeospira, Hindella, Whitfieldia,* and *Meristina* may be mentioned. *Atrypa* is a finely plicated shell with very convex brachial valve and without a hinge area. *Eospirifer* is the first of the line of the family Spiriferidae which had a very great development in the later Paleozoic and includes many valuable

index fossils. The spirifers are transversely elongate, generally plicated shells with a well-developed cardinal area and laterally extending internal spires.

More than 3,000 species of brachiopods are known from Ordovician and Silurian rocks of the world. The Silurian of America contains not less than 89 genera and 652 species.

Pelecypods

General Character.—Pelecypods are bivalved aquatic animals with a bilaterally symmetrical body, fairly well-developed digestive, circulatory, and nervous systems, and a muscular foot that may be used in locomotion. They have no head, in this and some other characters being more primitive, or degenerate, than the gastropods (snails) and cephalopods, which are grouped with pelecypods in the phylum Mollusca. In most pelecypods the membranous mantle that encloses the body and secretes the shell is extended backward out of the shell and forms two tubes (*siphons*). These carry a current of water, the inflowing one containing oxygen for respiration and microscopic organic matter for food, the outflowing one removing the waste products. The tubes can be drawn inside the shell, except in cases where they are unusually elongated. The majority of this group of invertebrates live on the bottom of the shallower parts of the sea, but some, like the mussels, have become adapted to fresh waters. They may crawl about slowly or burrow into mud, sand, or in some cases even into wood and stone. The scallop (*Pecten*) can swim a little by clapping its valves together and by forcing water alternately from one side and the other.

The two valves of the pelecypod are typically equal in size and symmetrical one with the other; they are carried, respectively, on the right and left sides of the animal, the line of hingement being dorsal. This is very different from the two valves of the brachiopod, which are respectively dorsal and ventral, one larger than the other, and each valve with equal symmetrical halves. The foot of the pelecypod projects forward on the ventral side between the valves, and the siphons backward. The beak of each valve is generally, but not always, pointed anteriorly and located in front of the mid-length of the shell. By this and other means the fossil shell may be oriented readily. The valves are held together in most pelecypods by two large muscles (*adductors*), but in some, like the oyster, there is only one adductor muscle. The valves are fastened together at the hinge by an elastic ligament, which, if external, is placed under tension and, if internal, under compression, when the muscles close the shell. When the muscles relax, the shell springs open automatically. Articulation of the two valves is aided in very many species by different types of teeth and sockets along the hinge line, the interlocking of these obviously serving to hinder slipping or twisting of one valve on the other. The external ornamentation

comprises more or less distinct concentric growth lines, projecting lamellae, ridges, ribs, folds, nodes, and spines. Certain fossil species have a subtriangular area (*cardinal area*) set off by a slight groove between the beak and hinge line; in others and in many living forms there is a heart-shaped area (*lunule*) bounded by a ridge or groove in front of the

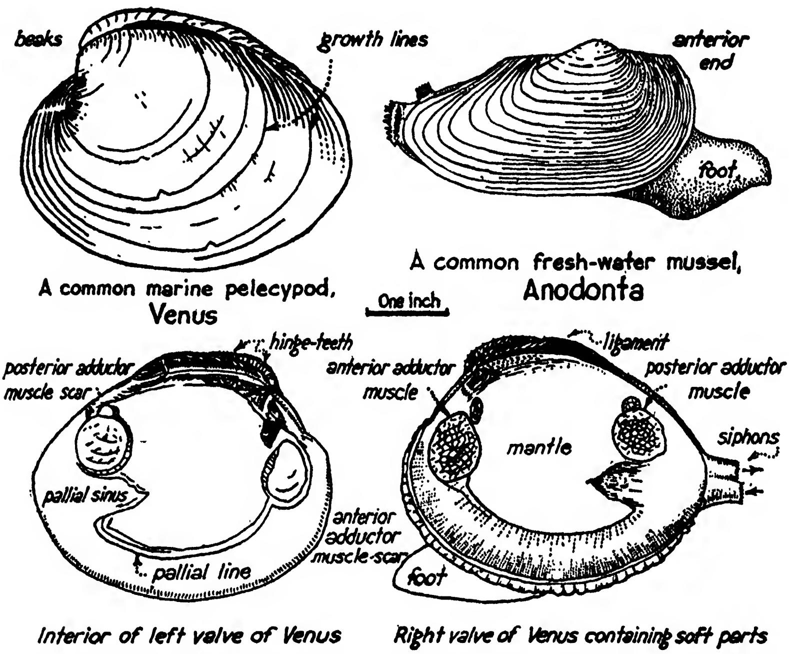


FIG. 117.—Drawings showing form and structural features of pelecypods. (*Modified from Winifred Goldring, New York State Museum.*)

beaks, and a more elongated one (*escutcheon*) extending backward from the beaks.

On the inside of the shell are found the scars of attachment of the muscles. A slightly impressed line (*pallial line*), marking the place of attachment of the mantle, is noticeable not far from the ventral border of many pelecypods. A strong indentation of this line (*pallial sinus*) in some marks the place where the siphons are drawn into the shell. These internal features show very clearly on some fossil molds. The fact that the inner pearly layer of pelecypod shells—in some cases nearly the whole shell—consists of aragonite explains the frequent removal of the shell substance by solution, for aragonite, though identical with calcite in composition, is more soluble. In collecting fossils, one often finds that brachiopods and other shells made up of calcite are well preserved, while pelecypods and gastropods, whose original shell was aragonite, are represented only by molds.

The structures of the hinge region, musculature, and general form of the shell are chief features used in classifying the pelecypods. In spite of a wide variety of forms, the group has been rather conservative throughout its long period of existence, with few lines of special development.

Occurrence of Pelecypods in Early Paleozoic Rocks.—The oldest undoubted pelecypods occur in Middle Ordovician beds where several genera suddenly make their appearance. These are rather archaic, generalized types that attained a climax in the medial and later parts of Ordovician time. They are mainly characterized

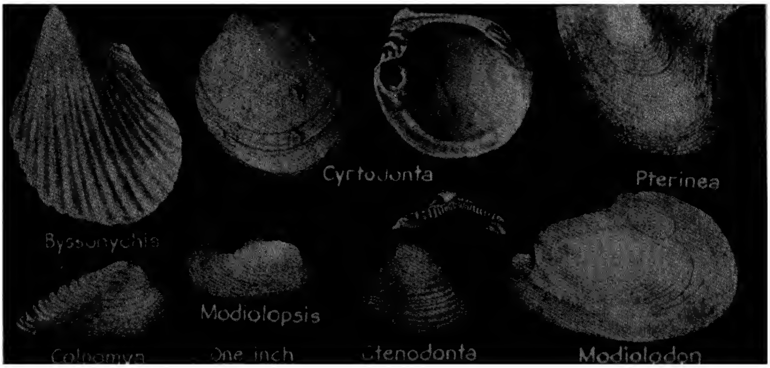


FIG. 118.—Some representative types of Ordovician pelecypods.

by the presence of a large number of simple, similar teeth along the hinge line, which is a primitive type of dentition (*taxodont*). Some of the characteristic types were prominently ribbed and had a large winglike expansion on one side of the beak (*Ambonychia*, *Byssonychia*). Others were much like the common mussel.

The Silurian contains fairly numerous fossil pelecypods, mostly belonging to genera slightly different from those of the preceding period. More than 75 kinds are known from the Silurian of the island of Gotland, in the Baltic. In general, however, the pelecypods of Paleozoic time were a little-changing group, less important to the stratigrapher and paleontologist than many others. The American Ordovician contains approximately 51 genera and 381 species, the Silurian 69 genera and 301 species.

Gastropods

General Character.—The gastropods, or snails, have a distinct head which carries mouth, eyes, ears, and tentacles. They are also distinguished by having a broad foot, on which they may crawl slowly about, and by the possession of a single spirally coiled or cap-shaped shell, on account of which they are frequently termed univalves. Some gastropods, however, have no shell at all. The mouth is armed with horny plates and a rasplike process (*radula*). The esophagus leads into a long coiled intestine, surrounded by a large liver, kidneys, and various

glands. A heart and many branching blood vessels make up the circulatory system, and two cerebral and numerous other paired ganglia, with their connections, compose the nervous system. Most gastropods have tufted or leaflike gills, originally paired, but usually becoming single by the atrophy of one. Reproductive organs are specialized. Gastropods are most abundant in the shallow seas, but they live also in

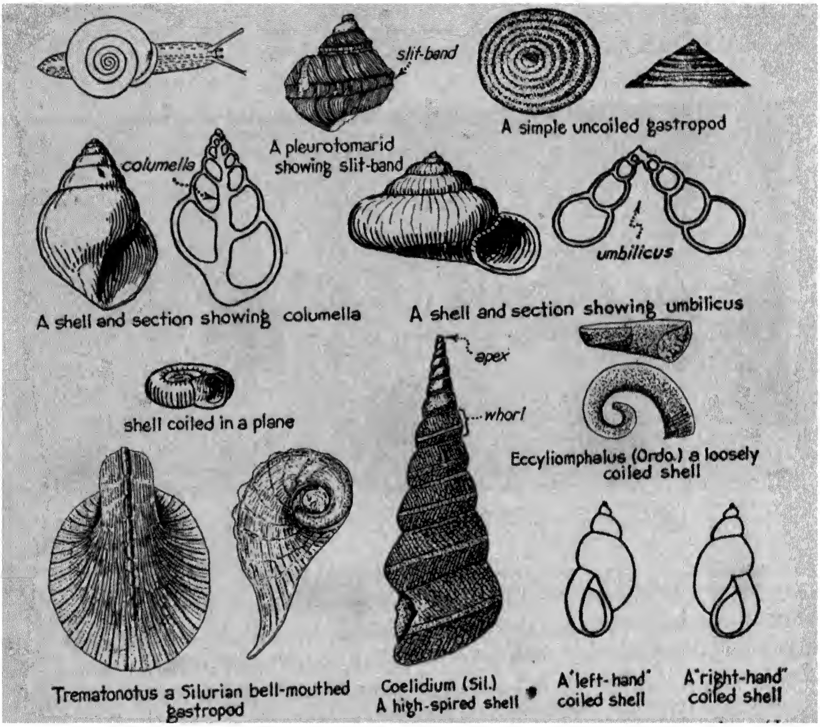


FIG. 119.—Drawings showing form and structural features of gastropods. (*In part, from Winifred Goldring, New York State Museum.*)

fresh waters and many are air breathers. They feed mostly on plants but some, including the drills, which can bore a neat round hole through other shells, are carnivorous. A few are scavengers.

The shell of the gastropod, secreted by the mantle on the dorsal side of the body, consists essentially of calcium carbonate in the form of aragonite and hence, like the pearly shell substance in pelecypods, is subject to solution or alteration rather readily in fossilization. The shell is spirally twisted or in some cases consists of an uncoiled cone. Generally, the spire is strongly elevated and screwlike, being carried on the back of the animal with the apex pointed upward and backward, and the aperture downward and forward. Most shells are right-handed; that is, the aperture when held downward and facing the observer is on the

right side. A few are left-handed. Some shells are coiled in a plane. Each complete coil is termed a *whorl*. The whorls may wind around a solid axial pillar (*columella*) or leave an open space (*umbilicus*). The aperture is generally rounded but may be notched by canals carrying the siphon which conducts water to the gills, and the anal tube. The position and character of these notches are frequently indicated on the earlier-formed whorls by the configuration of the shell and by deflection of the growth lines. External ornamentation is highly varied, consisting of revolving or transverse lines, grooves, ribs, frills, or of nodes or spines. In addition, many gastropod shells are beautifully decorated with a diversity of brilliant or delicate hues and patterns.

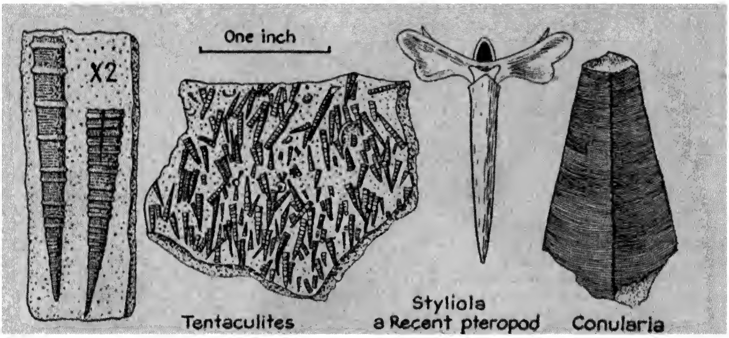


FIG. 120.—Conularids and a pteropod. (*Winifred Goldring, New York State Museum.*)

The body of the gastropod is united to the shell by muscular attachment, and generally the animal may draw itself entirely inside for protection. In many species an accessory plate (*operculum*) secreted by the foot then closes the aperture. This plate is commonly composed of horny material and is not fossilized, but rarely it is calcareous and may be preserved.

A subordinate division among the gastropods, which, however, was very important in parts of Early Paleozoic time, is that of the *pteropods*. These are rather small, free-swimming forms in which the foot is modified into two winglike fins. The shell is generally a narrow and straight pointed tube that is circular or triangular in cross-section. Somewhat similar are the *conularids*, which have a shell that is rounded or quadrangular in section. It is possible that these last may be a type of worm.

Occurrence of Gastropods in Early Paleozoic Rocks.—Gastropods are known from earliest Paleozoic time down to the present, their number and variety gradually increasing until they probably now enjoy their maximum vigor. More than twenty thousand Recent species are known.

Cambrian. At the base of the Cambrian the genera are small, archaic forms that are mostly cap-shaped and exhibit only slight tendency to coiling. Nevertheless, the

gastropods are outranked only by trilobites and brachiopods in number of known Cambrian fossils. In some of the deposits of this period, straight-shelled pteropods (such as *Hyolithes*) and shorter, less flaring tubes (*Salterella*) were numerous. Coiled gastropods began to predominate in the later Cambrian, and in some of the Ozarkian formations they outnumber all other kinds of organisms.

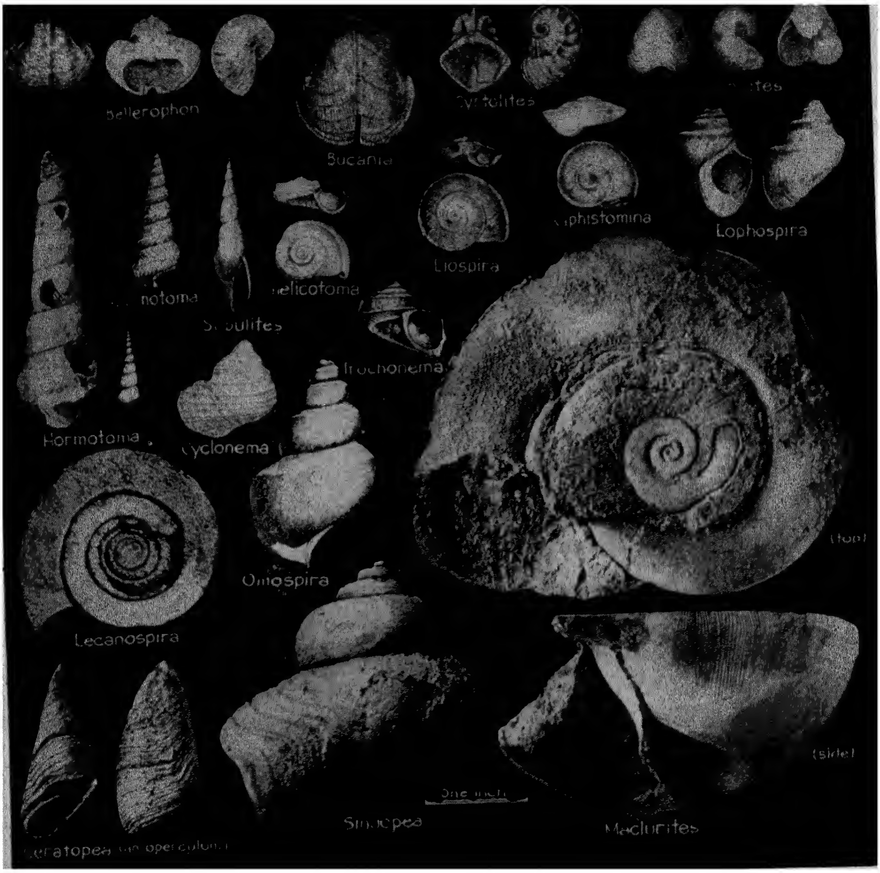


FIG. 121.—Some representative types of Upper Cambrian (Ozarkian) and Ordovician gastropods.

Ordovician.—During Ordovician time there was a very great increase in the number, variety, and relative importance of the gastropods. In some of the Canadian strata they afford the best index fossils available. Very prominent were the flat or low-spired shells, some with right-handed (*Ophileta*) and some with left-handed coils (*Maclurites*, *Lecanospira*). Moderately elevated, well-ornamented spiral shells (*pleurotomarids*) and some very high, screwlike spires (*Hormotoma*) are also present. The Mohawkian and Cincinnatian divisions also contain common representatives of this class, but they are by no means so important relatively. This is largely but not entirely due to the tremendous increase in the number and variety of other invertebrates. The Ordovician was a time of considerable prominence of gastropods, however, as indicated by the number of American types, about 80 genera and 675 species.

Silurian species are mostly distinct from those of the Ordovician, but there is no important change in type. The aggregate number of species is large. The chief types are (1) coiled in a single plane (*Bellerophon* and allies), (2) coiled in an elevated spire (like *Pleurotomaria*), both with a prominent notch or slit in the outer margins, and (3) various coiled shells with entire margins. Some Silurian formations contain enormous numbers of the fossils called *Tentaculites*, which are slender, thick-walled tubes surrounded by rings. One of the Upper Silurian formations of New York was known to older geologists as the *Tentaculite* limestone. The Silurian of North America contains at least 68 genera and 342 species of gastropods.

Cephalopods

General Character.—The cephalopods are the most highly organized class of mollusks, the largest and most powerful of all invertebrate animals, and one of the most important groups of fossils. The best-

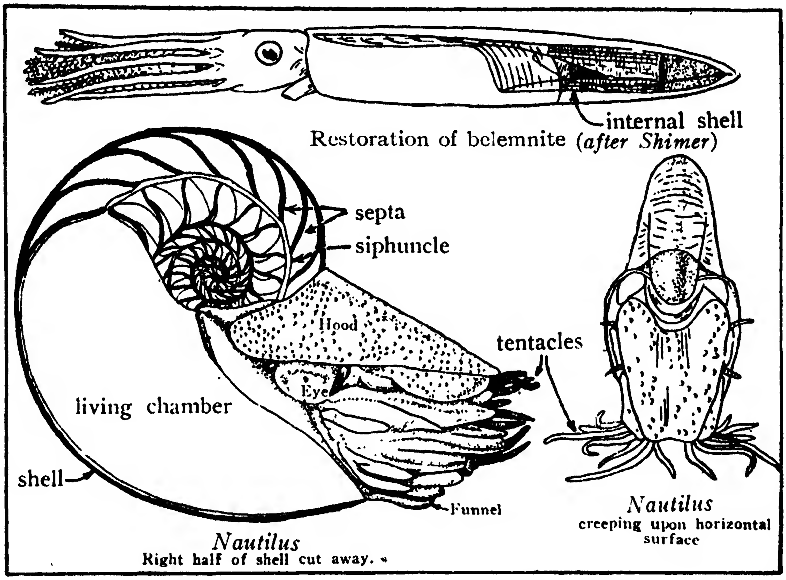


Fig. 122.—Drawings showing structural characters of a cephalopod with external shell (Nautilus) and one with internal shell (belemnite). (*Winifred Goldring, New York State Museum.*)

known living cephalopods are the pearly Nautilus which has a coiled, many-chambered shell, and the cuttlefishes, some of which have internal shelly structures. The head is well defined in most types and is provided with large eyes. The mouth contains jaws armed with a powerful horny beak and is surrounded by fleshy tentacles that are used in grasping objects. Among cuttlefishes, the tentacles bear strong sucker disks and hooks. The foot is transformed into a muscular funnel-shaped swimming organ through which water may be ejected so as to propel the cephalopod backward or sideward rapidly. Cephalopods breathe by gills and are exclusively marine. The nervous, circulatory, digestive,

and reproductive systems and the sense organs are all specialized and well developed.

There are two classes of cephalopods: (1) the *tetrabranchiates*, which have four gills and a chambered external shell, and (2) the *dibranchiates*, which have two gills and an internal shell, or none at all (excepting the female argonaut that has a thin, unchambered external shell). The first group is represented by thousands of fossil species, but only one, the Nautilus, still living; the second had a great development in Mesozoic time and includes a variety of living species. Only the primitive Nautilus-like shells, by which the cephalopods are represented in the older Paleozoic rocks, will be considered now.

Nautiloid Cephalopods.—The shell of the Nautilus is coiled in a plane and is bilaterally symmetrical. In life the aperture is directed

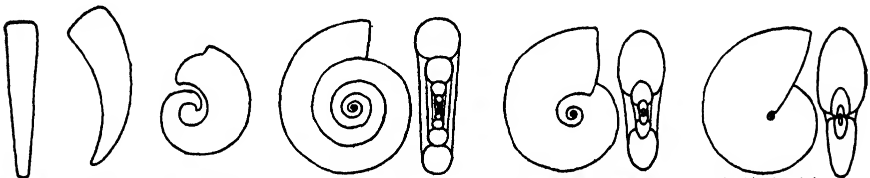


FIG. 123.—Diagram illustrating form of cephalopod shells as regards type of coiling. The three tight-coiled shells at right are shown in side view and cross-section.

forward, the shell twisting spirally backward and upward above the animal. Accordingly, the outer, convex part of the coiled tube is ventral, and the inner, concave part, dorsal. In side view only the last-formed coil (*whorl*) of the shell may be seen, for in the Nautilus each coil extends laterally so as to envelope and conceal the inner ones. The cross-section of each embracing whorl is therefore strongly crescentic. This type of shell is said to be deeply *involute* and it is evidently an advanced or specialized form of coiling. Among fossil nautiloids there are many examples in which the outer whorl only partly embraces the inner, and many in which the coils are barely in contact at their outer and inner margins. Then there are coiled shells in which the whorls do not touch. There are also curved but uncoiled shells, and finally the most primitive type of all, which is straight.

The body of the Nautilus occupies only the end portion of the outer whorl, this part of the shell being known as the body chamber. At the inner end of the body chamber is a cross plate (*septum*), that is concave toward the aperture, and at regular short spaces throughout the unoccupied parts of the shell are similar partitions that were formed at successive stages in the growth of the animal. These septa and the chambers into which they divide the Nautilus shell are characteristic features which serve to distinguish it very readily from that of planospirally coiled

gastropods. Observation shows that each septum is pierced by a round opening which provides passage for a tube (*siphon*) that extends back to the embryonic chamber in the center of the shell. In many of the ancient nautiloids the siphon was encased in a calcareous tube (*siphuncle*), which, of course, may be preserved in the fossils. The junctions of the septa with the outer wall of the shell are termed *sutures;* they cannot be seen from the exterior unless the outer shell is broken or worn away. The sutures of Early Paleozoic cephalopods are straight or gently curved, but those of later time became angulated and extremely complex in pattern. External ornamentation consists merely of color bands and faint curving growth lines in the modern Nautilus. The majority of fossil nautiloids have smooth shells, but some had strong ribs or spines, and in a few cases indications of a color pattern have been preserved.

Occurrence of Cephalopods in Early Paleozoic Deposits. *Cambrian.*—The sudden advent of a varied, well-advanced cephalopod fauna in the Upper Cambrian (Ozarkian) beds indicates the existence and gradual development of this important group in some region during earlier Cambrian time. The small straight-shelled forms called *Volborthella* and *Salterella*, which occur in Lower Cambrian beds, are regarded by some paleontologists as primitive cephalopods, but there are reasons for doubting that they properly belong here.

Ordovician.—Nautiloid cephalopods are numerous in some of the Ordovician formations, appearing commonly first in the lower (Canadian) part of the system. Straight (*Orthoceras*, *Endoceras*) and slightly curved (*Cyrtoceras*) shells greatly predominate, but there are several genera of loosely coiled and close-coiled shells. In one group (Lituitidae) there is evidence of the decadence of a former tightly coiled stock, for the shells are well coiled in the youthful stages but revert to the primitive straight form in the adult stage. In another (Plectoceratidae) the growth of the shell follows roughly the elevated spiral form of a gastropod, an even greater deviation from the typical cephalopod shell form. The Ordovician straight-shelled cephalopods are characterized, in general, by the large size of the siphuncle, by the filling of it in many genera with mineral deposits, and by the large size of some of the shells, estimated to have had a length up to 15 feet. The majority of these shells were smooth externally, but several bore transverse ribs, and in mid-Ordovician time some with longitudinal ridges also appeared. In none of the coiled cephalopods is there appreciable lateral overlapping of a whorl on the one next within, each part of the shell being therefore subcircular in cross-section. There were upwards of 50 genera and 350 species of cephalopods in the Ordovician of North America.

Silurian.—The culmination of nautiloid cephalopods—those with relatively simple septa and sutures—was reached in Silurian time when the greatest number and variety of these animals existed. On the average they were not so large, perhaps, as their predecessors, and the size of the siphuncle and the prevalence of filling deposits were notably reduced. A peculiarity of several genera (*Trimeroceras*, *Gomphoceras*, and others) was the constriction of the aperture to an opening so narrow that movements of the animal must have been greatly hindered. Such a specialization, like the screw-shaped spiral shells which were more numerous in the Silurian than other periods, is a character indicating decline or abnormal specialization, and presaging extinction of these branches of the nautiloid stock. The proportion of coiled shells was greatly increased in Silurian time, the number approximately equaling that of the straight and curved types. Before the close of the period, the first of the more

complexly sutured cephalopods (ammonoids), to be described later, had appeared. The American Silurian contains about 41 genera and 240 species of cephalopods.

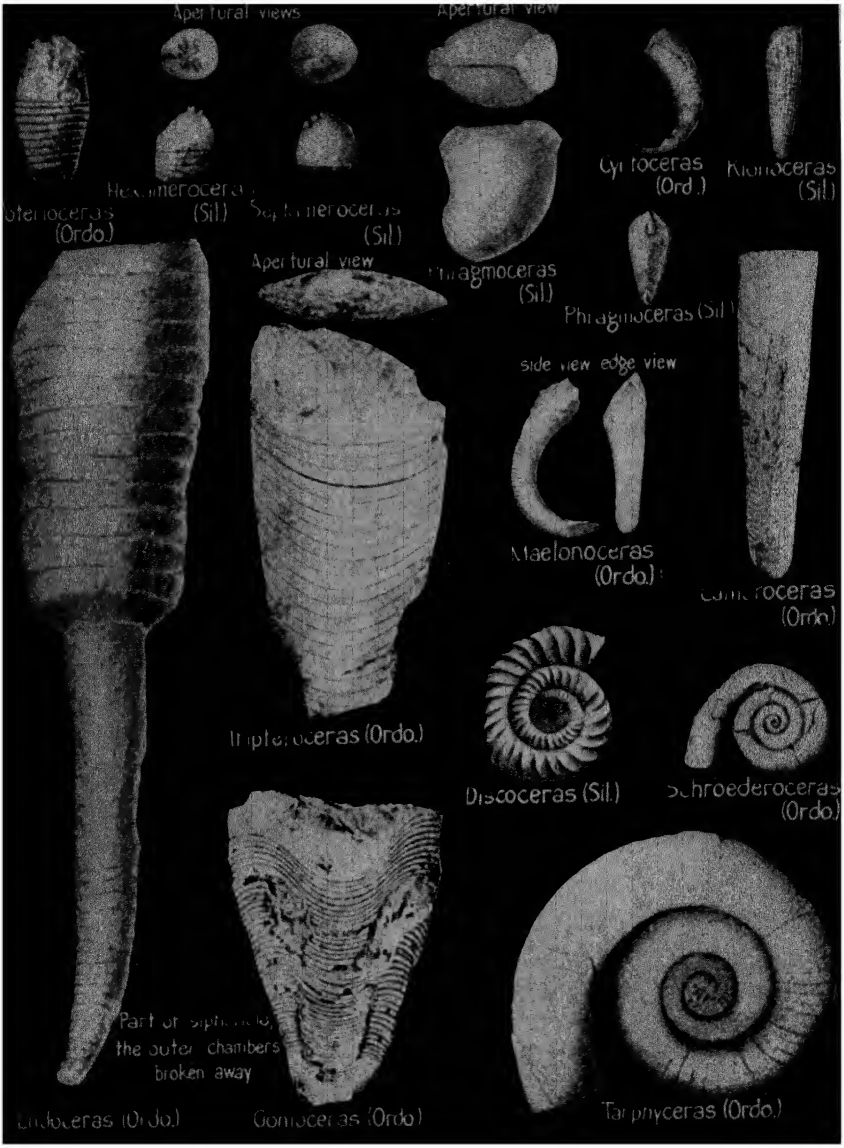


FIG. 124.—Some representative types of Early Paleozoic cephalopods. (About one-fourth natural size.)

Trilobites

General Character.—The most interesting of all invertebrate fossils to the average person are the trilobites. This is partly due perhaps to

the easily recognized character of the head, eyes, segmented body, and tail, and partly to the obvious biologic advancement and approach to such familiar creatures as lobsters, crabs, and insects. Indeed, trilobites are probably the direct or indirect ancestors of all other joint-legged invertebrates (Arthropoda) which surpass in number of species all other classes of animals combined. For this reason, and because the trilobites are very numerous and valuable index fossils in many Paleozoic formations, they occupy a position of importance.

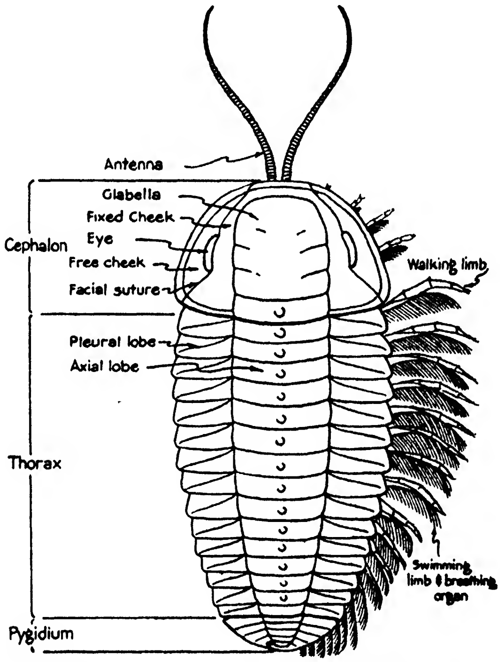


FIG. 125.—Diagram showing parts of a trilobite (*Triarthrus*, Ordovician). The limbs, shown on one side of the test, are preserved only in most exceptional cases.

Trilobites were protected on the dorsal side by a hard shelly structure consisting of chitin impregnated by calcium carbonate. The shell, or test, is longitudinally three-lobed, with an axial and two side (*pleural*) regions that are commonly well defined on head (*cephalon*), thorax, and tail (*pygidium*). The dorsal test is the only part commonly preserved, and, since it is rather easily separated into segments, one finds these fragments much more frequently than a complete test. As shown by a few remarkably well-preserved fossils, these animals had delicate antennae, numerous legs that were used for crawling or swimming, and breathing organs.

The central lobe of the head (*glabella*) is generally well defined. Typically, it is divided transversely into five lobes which represent the

original segments that consolidated to form the head and correspond to the five pairs of appendages on the ventral side of the head. The lateral portions of the head are each divided by a line of parting (*facial suture*) into two parts, an inner (*fixed cheek*) attached to the glabella and an outer (*free cheek*) that carries the eyes. In the most primitive order of trilobites (Hypoparia) the fixed cheeks make up all or nearly all of the dorsal side of the head shield, excepting the glabella, the facial suture being marginal or ventral. In the more advanced orders the free cheek shows clearly on the dorsal side, the suture intersecting the posterior margin of the cephalon (Opisthoparia) or the lateral margin (Proparia)

FIG. 126.—A small slab of Middle Cambrian rock from Newfoundland that contains large numbers of disjointed head and tail shields of the minute trilobite, *Eodiscus*. (*C. E. Resser, U. S. National Museum.*)

in advance of the posterolateral angle (*genal angle*), which in some cases is prolonged in a spine. Most trilobites had a pair of slightly raised, outward-facing compound eyes with numerous facets, and there is evidence in some of a median simple eye on the rear lobe of the glabella. The number of facets of the compound eyes is surprisingly great, the maximum being about 15,000. Some trilobites were blind. The segments of the thorax were jointed and permitted slight movement, but flexibility sufficient to bring the tail under the head and thus protect the vulnerable ventral parts was apparently not developed in the earliest, most primitive genera. The pygidium, like the head shield, is evidently formed from several segments, for its superficial markings and the paired appendages beneath it seem to indicate ancestral separated segments.

Evolutionary Characters.—Stages in the development of the trilobite individual are determinable by means of the successively cast-off or

molted shells. During the larval (*protaspis*) stage when only a cephalon and a pygidium were present, there were commonly several molts; during the adolescent stage there were molts at the time of adding each thoracic segment; and during adult life there were further molts that permitted increase in size but did not increase the number of segments. The characters exhibited during these changes are significant in establishing the direction of evolutionary modification in the different groups of trilobites, for the life history of the individual recapitulates more or less completely the history of the race. In the Cambrian there are numerous adult trilobites (*Agnostus, Eodiscus*) that have a form corresponding to a very early postlarval stage in more advanced species. As shown by studies of growth stages, and by the order in geologic time of the development of various adult characters, the features that chiefly mark evolution among the trilobites are (1) position of the facial suture, (2) nature and location of the eyes, (3) changes in the glabella, (4) suppression or overdevelopment of anatomical features, and (5) ornamentation.

Occurrence of Trilobites in Early Paleozoic Rocks. *Cambrian.*—Trilobites not only occur in the oldest known fossil-bearing beds of Cambrian age, but they are the most abundant class of organisms. Their complexity of structure and variety of form indicate clearly that the beginning of the trilobites must date back into pre-Cambrian time. More than 65 genera and several hundred species have been described from the Cambrian, and it is estimated that over 1,000 undescribed species are contained in collections of the United States National Museum (Resser). As compared with trilobites of later Paleozoic time, those of the Cambrian show several distinguishing features. (1) Very small, larva-like genera with subequal, relatively large head and tail shields and only two or three thoracic segments are common (Agnostidae, Eodiscidae). (2) Another more heterogeneous group, characterized by a long body with a large number of thoracic segments and a very small pygidium, is prominent (Conocoryphidae, Mesonacidae, Paradoxidae, Olenidae). (3) Species without eyes, or only simple eyes, are numerous, and the majority of those with compound eyes have very small ones set well away from the glabella. (4) The glabella commonly shows a distinct division into lobes, and the longitudinal three-lobed character of the carapace is always strongly defined. (5) Surface ornamentation and excessive development of spines are rare. On the other hand, there are numerous examples of specialization. Some of the Lower Cambrian trilobites had very long spines and several genera are distinguished by unusually large caudal shields. In size, the trilobites of this period ranged from shells less than ¼ inch in length to more than 18 inches (*Paradoxides* and *Wanneria*).

Ordovician.—The greatest profusion and variety of trilobites appear in Ordovician rocks, for this period marks the culmination of the class. Seven of the Cambrian families and fifteen new ones are represented, which means that every trilobite family except those restricted to the Cambrian is accounted for. Among the Hypoparia are several interesting forms with a very large head shield bearing a broad pitted brim and long genal spines (*Harpes, Cryptolithus*), while only a few of the minute larviform species remain. In one group (*Ampyx*) the glabella carries a prominent forward or upward projecting spine. The Opisthoparia contain types that are long-bodied and fairly conservative (*Triarthrus*); specialized in the development of snoutlike anterior projections of the cephalon (*Megalaspis, Hoplolichas*), or bizarre spinose ornamentation (*Acidaspis, Ceratocephala*); and decadent in the obsolescence or loss of typical

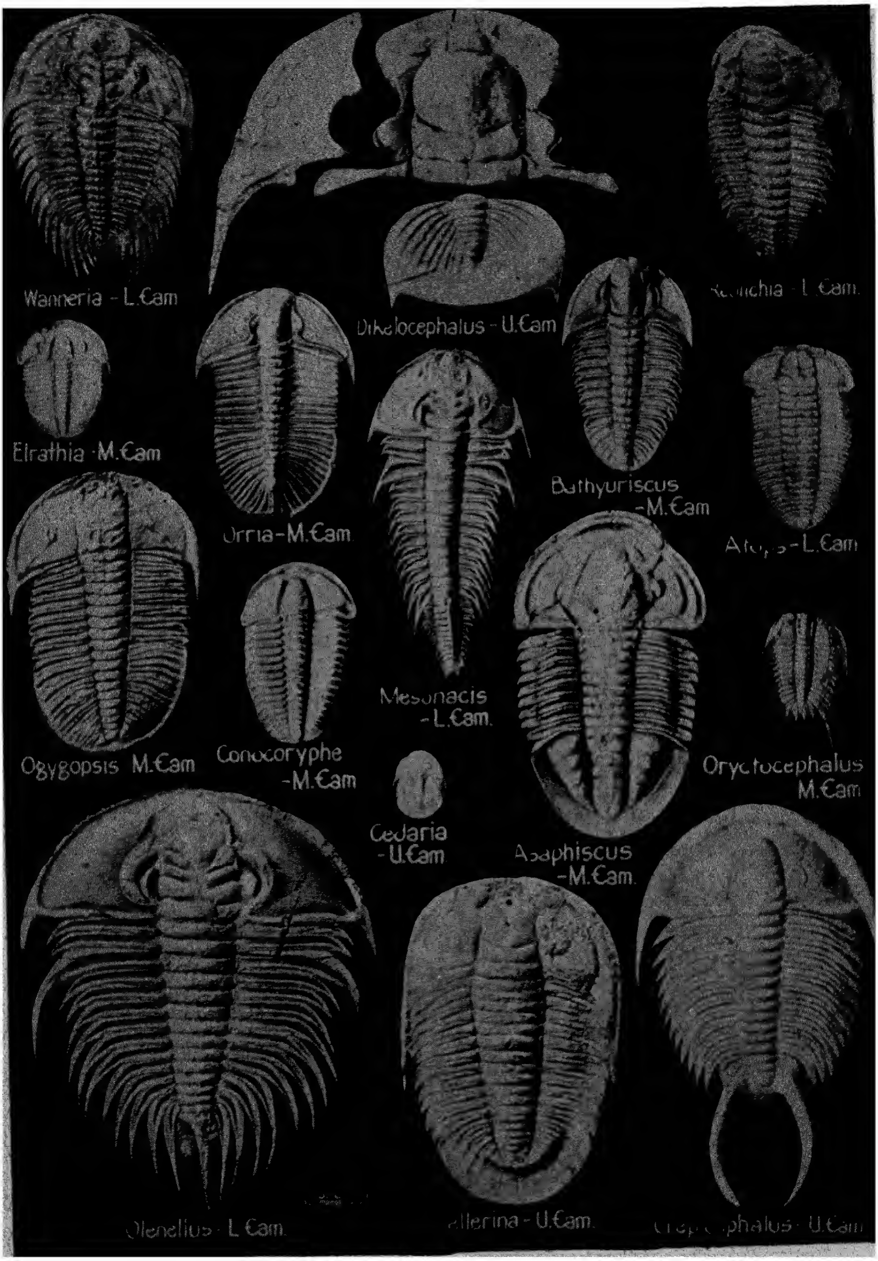


Fig. 127.—Some representative types of Cambrian trilobites.

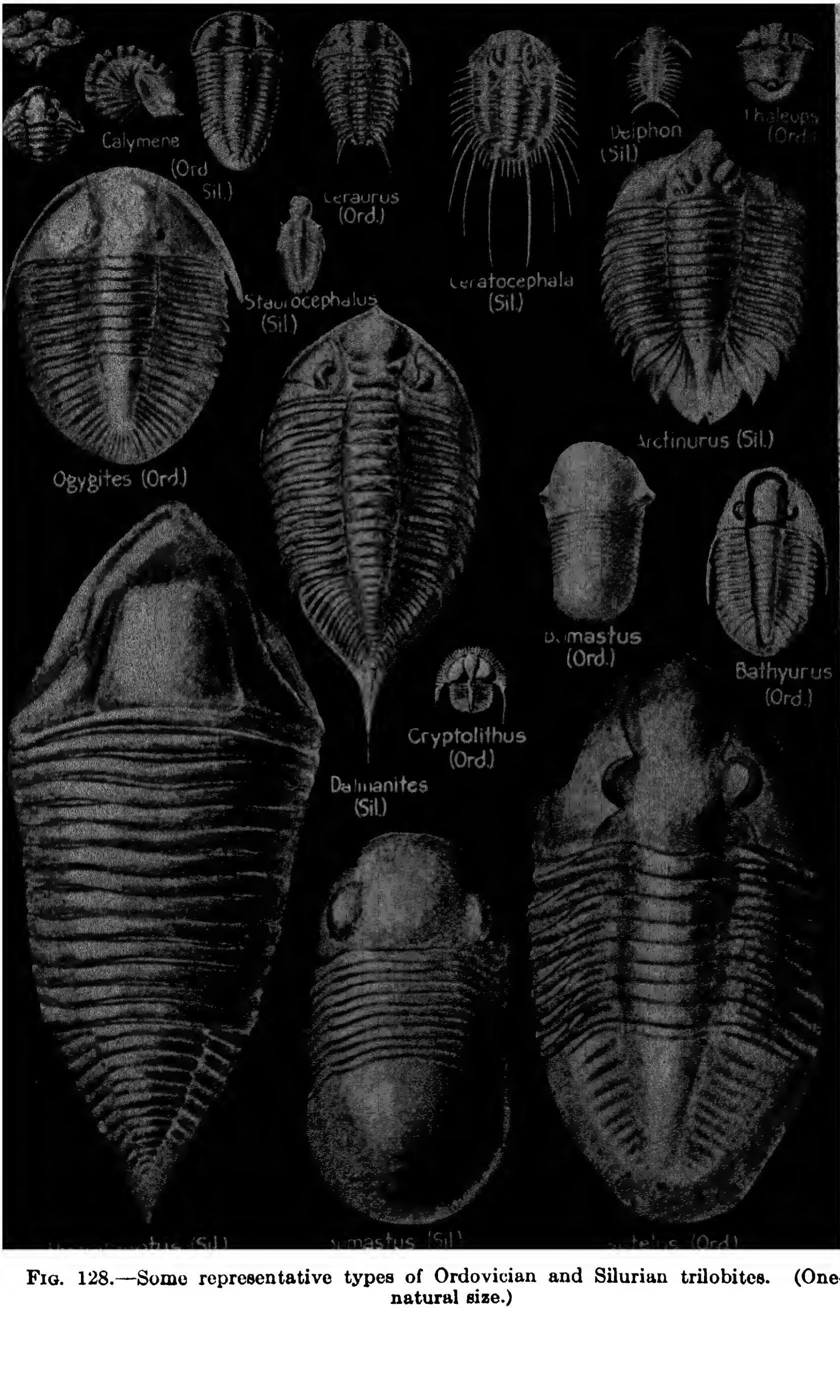


FIG. 128.—Some representative types of Ordovician and Silurian trilobites. (One-half natural size.)

features of the head and tail (*Illaenus, Bumastus*). In some genera there is no trace of lobation of the glabella, and the glabella itself may become indistinct. In *Cyclopyge* there is a remarkable development of the eyes which are expanded to cover the entire outer thirds of the cephalon. The Opisthoparia are more abundant than in any later period. In the majority of this group the structural characters are conservative; the glabella is distinct and generally furrowed, the eyes are commonly small, and the pygidium bears clear surficial segmentation. Almost all of the Ordovician trilobites were able to roll up so as to conceal the ventral region, and many fossils in this rolled-up position are found. The largest known trilobite is from Ordovician strata in Europe. It had a length of about 27 inches. Some American specimens (*Isotelus maximus*) attained a length of nearly 24 inches.

Silurian.—The Silurian history of the trilobites is marked mainly by the disappearance of certain of the earlier genera and families, and the relatively greater prominence of the proparian group. There were only half as many families in the Silurian as in the Ordovician; the number of genera was reduced about one-half (99 to 47) and the number of species from about 390 to 180. The lines of development that have been noted continued. One large group was conservative, another carried to an extreme the tendency to overdevelop certain features or to become spinose, and a third lost almost all trace of the fundamental trilobate plan of the shell. Some of the most common and important genera are *Illaenus, Lichas, Calymene, Homalonotus, Cheirurus,* and *Dalmanites.*

Ostracodes

Ostracodes are minute, commonly microscopic, bivalve crustaceans that (excepting one or two families) are restricted to the sea. They occur in vast numbers and a study of the microscopic fossils that may be washed out of most marine shale or shaly limestone deposits shows that ostracodes are common and highly varied in rocks of all ages back to the Early Ordovician. The majority of genera and species are not long-ranging vertically, which fact, together with wide geographic distribution and large numbers, makes them valuable index fossils. In recent years they have served especially in helping to identify and correlate the rocks penetrated in oil wells, for, in spite of the action of drilling tools, many perfect specimens can often be found in the well cuttings.

The valves of the ostracode shell are generally somewhat elliptical in outline, commonly with a straight hinge line, and with a diversity of surface markings that consist chiefly of raised lobes and depressed grooves or pits. Some have a beautiful network surface ornamentation, broad flangelike frills, or projecting spines (see Fig. 207).

Ordovician and Silurian rocks contain an abundance of genera and species of ostracodes, and in some formations specimens may be collected by thousands. Ulrich and Bassler have recently described no less than 30 genera (17 new) and 228 species (215 new) of ostracodes from the Silurian of eastern North America.

Other Arthropods

Eurypterids.—The eurypterids are an interesting group of extinct arthropods which include the largest animals of this phylum, measuring up to 9 feet in length. The body was elongate, with a thin chitinous

segmented shell. The head region bore on the dorsal side a pair of large compound eyes and another pair of median simple eyes, and on the ventral side six pairs of appendages, some of which in certain forms were armed with pincers. The tail (*telson*) was long and pointed or flat and spatulate. The presence of gills shows that the eurypterids were aquatic, and the structure of the appendages indicates that they were mostly mud crawlers, though some were probably good swimmers. They are

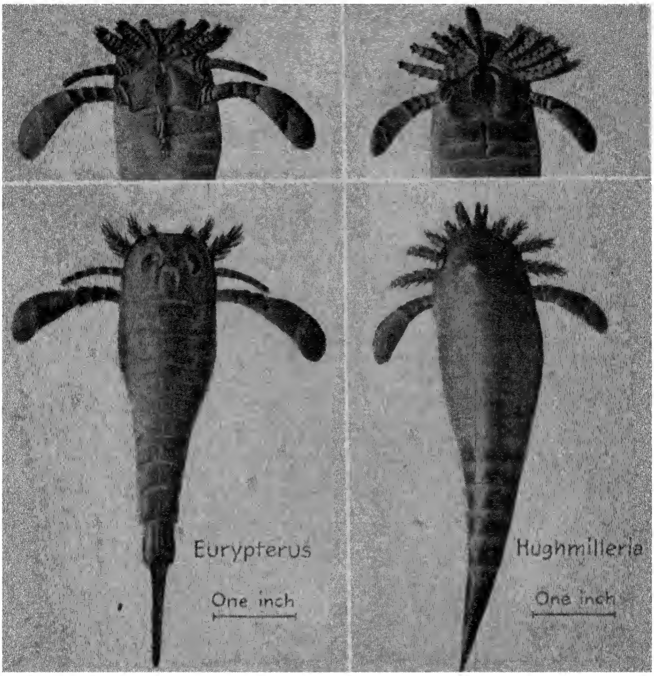


FIG. 129.—Upper Silurian eurypterids from New York. The upper views show the ventral side of the anterior region. (*From models by Rudolf Ruedemann in New York State Museum.*)

found associated with marine fossils in Cambrian, Ordovician, and Silurian rocks, but some appear to have become adapted to a brackish-water environment, and those known from the Pennsylvanian occur with a fresh-water fauna. One eurypterid is known in the Cambrian. Six genera and 16 species are reported from the Ordovician, and 8 genera and 35 species from the Silurian.

Scorpions.—A few specimens of scorpions, almost identical in appearance with modern examples, are found in Silurian strata of North America and northern Europe. The fossils indicate by certain structural features and by association that they were aquatic in habit, but it is clear that scorpions of Pennsylvanian age had become adapted to life on the lands, breathing air.

Fishes

The earliest known fish remains, representing the very primitive group called *ostracoderms*, occur in Upper Ordovician sandstone (Harding) of eastern Colorado and Wyoming. These are bony fragments that reveal little of the nature of the fishes themselves, but in later Paleozoic strata both marine and fresh-water species are well shown. The Silurian rocks contain scattered bony spines that were borne by some of the early sharklike animals. More detailed consideration of fossil fishes will be reserved for the chapter on life of the later Paleozoic periods.

SUMMARY OF LIFE EVOLUTION

Cambrian Period.—The dominant animals of Cambrian time were the trilobites, fossil remains of which outnumber all other classes. Brachio-

FIG. 130.—A large slab of ripple-marked Upper Cambrian sandstone from eastern New York, showing peculiar trails thought to have been made by a very large annelid worm. (*U. S. National Museum.*)

pods were second in importance, and gastropods third. Archeocyathinae were important locally, building reefs that are as large as any known in the Paleozoic. Several types of sponges are found, and worm borings are abundant in some beds. The rarity of hydrozoans and echinoderms, and the absence of bryozoans and pelecypods, is noteworthy, but, in view of the biologically advanced character of these classes and their variety as seen in Ordovician rocks, it can hardly be assumed that they were actually nonexistent in the Cambrian period. Indeed, it is probable that all originated in pre-Cambrian time, either living in regions other than those where fossiliferous Cambrian occurs or, more plausibly, failing to leave a fossil record because of a lack of hard parts. The sudden appearance and advanced nature of the known Cambrian faunas, especially of the trilobites, present a similar problem which is explainable in part if we accept the opinion of some geologists that most of the known pre-Cambrian sediments are nonmarine. However, this assumption appears to have doubtful validity.

A well-defined differentiation of faunal provinces first appears in the Cambrian. It is controlled by the distribution of the shallow seas. The dominant fossils characteristic of these provinces and also the chief zone fossils of the Cambrian are the trilobites. In each province and each stratigraphic series there are, in many cases, trilobite genera and species that are restricted to it. (1) The seas that invaded the Cordilleran and Appalachian troughs were mostly of northern origin; the faunas may be

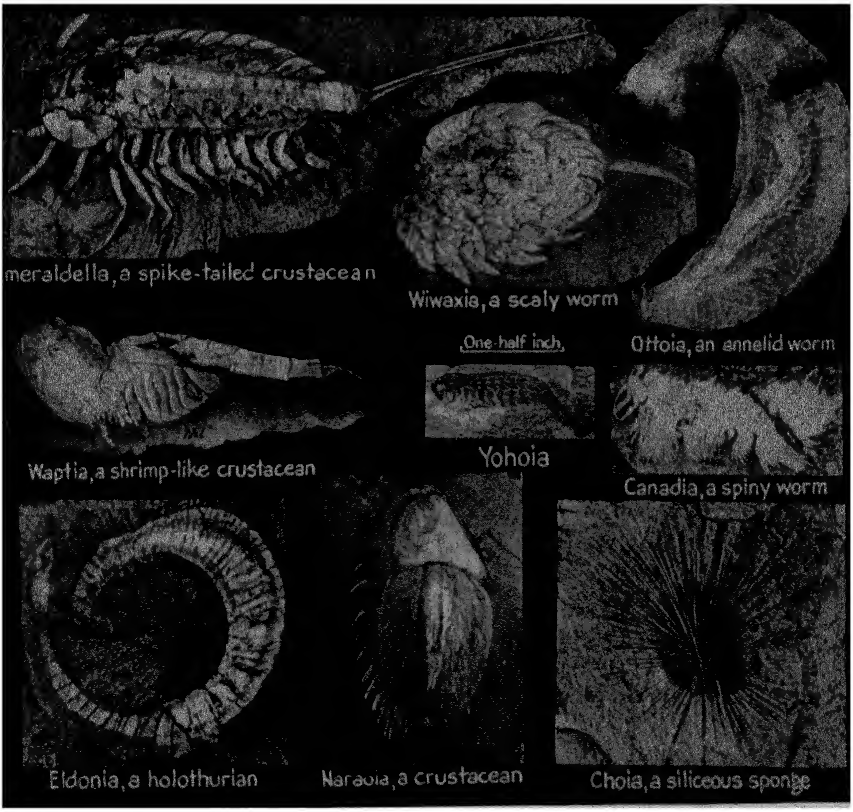


FIG. 131.—Fossils from the Middle Cambrian Burgess shale, British Columbia. (*C. D. Walcott.*)

termed Arctic. The trilobite family Mesonacidae, of which *Olenellus* is one of the most widespread and typical kinds, is characteristic of the Lower Cambrian of this province. Many genera in the Middle and Upper Cambrian faunas indicate an Arctic origin. (2) A Pacific fauna invaded eastern Asia and western North America. This contains a very prolific assemblage in which the trilobite genera *Redlichia* in the Lower Cambrian, *Dorypyge* in the Middle Cambrian, and *Crepicephalus* in the Upper Cambrian are especially characteristic. (3) The Atlantic fauna is represented in North America only in southeastern Newfoundland,

New Brunswick, Nova Scotia, and eastern Massachusetts. There are local occurrences of this fauna in the Middle Cambrian of Vermont and the Upper Cambrian of Alabama. Characteristic trilobite genera of this fauna are *Holmia* and *Callavia* in the Lower Cambrian, *Paradoxides* in the Middle Cambrian, and *Olenus* and *Peltura* in the Upper Cambrian.

The Burgess Shale Fauna.—Consideration of the life in Cambrian times calls for special mention of the remarkable fossil locality discovered by Walcott on the slopes of Mt. Wapta, about 3,000 feet above the town of Field, on the Canadian Pacific railway, in British Columbia. The fossils occur in the Middle Cambrian Burgess shale, about 7 feet thick. Thousands of specimens, representing some 75 genera and 140 species, have been collected. However, the interesting feature is not the number but the marvelous preservation and unusual character of the majority of the organ-

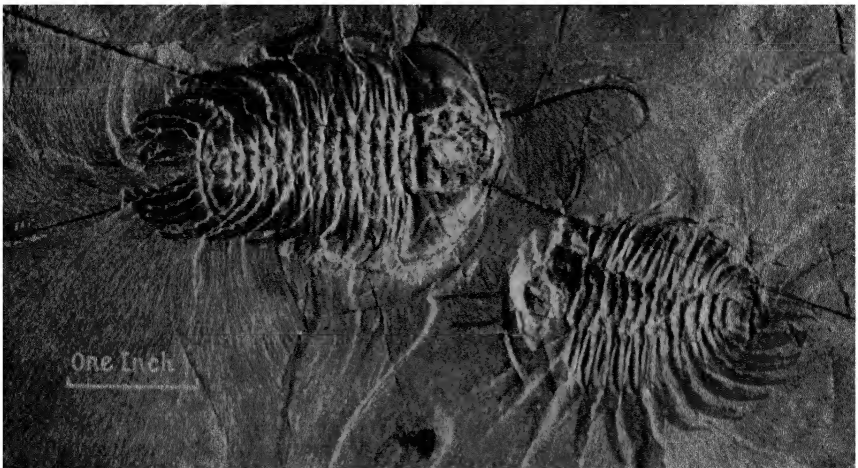


FIG. 132.—Two remarkable trilobite specimens (*Neolenus*) showing appendages in place. From the Middle Cambrian Burgess shale, British Columbia. (*C. E. Resser, U. S. National Museum.*)

isms. Many of them are entirely lacking in hard parts, yet delicate appendages and even internal structures are clearly shown. The nature of the shale which is a very fine-grained dark hard shale, suggests that this deposit accumulated in a stagnant, unoxygenated depression of the sea bottom where no scavenging animals or the usual decomposing bacteria could live. The fossilized creatures were almost all floaters or swimmers, living near the surface, and when they sank to the foul bottom ooze, even the soft-bodied jellyfish were nearly perfectly preserved. The fauna consists of sponges, worms, holothurians?, jellyfish, pteropods, trilobites, and a variety of other crustaceans; there are algae also. It affords an illuminating glimpse of the variety of life that is mostly missing from the paleontologic record.

Ordovician Period.—The life of Ordovician time is broadly characterized by appearance for the first time of representatives of all the invertebrate phyla, almost all in goodly numbers. The groups that composed the Cambrian faunas are distinguished by a variety of evolutional advances, and in each a larger number of species is known. The dominant classes, in the order of total number of different species, are

(1) gastropods, (2) brachiopods, (3) bryozoans, (4) trilobites, (5) pelecypods, (6) cephalopods, and (7) graptolites, all but the last having more than 350 species. This ranking is not necessarily the most significant, because some beds may contain millions of individuals of a single species which thus may dominate the fauna. The distinguishing structural characters of these groups in Ordovician time have been reviewed.

The main zone fossils in Ordovician deposits include several kinds of invertebrates, and calcareous algae of the type called *Cryptozoon*. The latter occurs especially in the basal part of the system, as well as in the Ozarkian. Gastropods of several sorts, chiefly flat-spired or coiled in a plane, are characteristic of some formations, and one very widespread zone is marked by the presence of a thick, cone-shaped gastropod operculum (*Ceratopea*). Among the brachiopods, bryozoans, and trilobites, there are numerous important index fossils, and in some cases the abundance of certain species aids in identifying a zone. Graptolites are especially useful in distinguishing the age of beds in which they occur, for they were widespread and abundant, but the species were mostly short-lived.

Faunal provinces are clearly recognized but changes in extent and in connection of the seas that invaded the continent complicate the record. At times of greatest marine inundation, free intermigration of bottom-living organisms was possible and the fauna took on a correspondingly cosmopolitan character. The regions of black shale deposition and abundant graptolite development, which were located mainly along the eastern side of the Appalachian geosyncline, are distinguished faunally from the interior seas in which different sediments, mainly limestone, were accumulated. This has been interpreted to mean that a land barrier separated these areas, but it may have been due partly or wholly to differences in environment that are not clearly understood.

The chief characteristics of Ordovician life are the profusion of marine invertebrates representing almost all classes, the great variety and biologic advancement as compared with Cambrian organisms, and the archaic character of several of the groups, especially cephalopods, echinoderms, and bryozoans, as compared with Silurian and later Paleozic time. The first fishlike animals are known from Ordovician rocks.

Silurian Period.—The faunas of Silurian time more closely resemble the Ordovician than those of the Ordovician resemble the Cambrian. The most noteworthy changes were (1) a marked increase of stromatoporoids and decrease of graptolites, (2) a tremendous increase among the corals, (3) a greater prominence of echinoderms, especially crinoids, (4) an advance of the brachiopods to a point near the acme of their career, and (5) a considerable decline of the trilobites. The number of gastropod species is little more than half that of the Ordovician, but this is not very significant. Some of the differences in numbers of described fossil species may be due to the fact that the Silurian is neither so thick nor so widespread in America as the Ordovician.

THE LATE PALEOZOIC SUBERA

CHAPTER XVI

FORMATIONS AND PHYSICAL HISTORY OF DEVONIAN TIME

The Devonian period, which introduces the Late Paleozoic subera, is an important chapter in earth history, for sedimentary deposits of this age several thousands of feet in thickness occur on each of the continents. The seas again invaded North America, covering it most extensively in the medial and late parts of the period. Fossils in the marine formations are commonly abundant and in many places they are exceptionally well preserved, attracting the special attention of collectors and paleontologists. Among interesting features in the record of this period are the extraordinary development of continental deposits, the appearance in these of the oldest known land flora, and the first evidence of land vertebrates. There are also many fossil fishes that throw light on evolution of the early vertebrates.

It is appropriate to mention here what we may term the human side of the Devonian, that is, the impress on geologic science and on man's thought in general that has come from studies of Devonian rocks and their contained fossils. These studies have been the special pursuit of several distinguished geologic workers. There is Hugh Miller of Scotland, stonemason by profession, who became interested in the fossil fishes and other organic remains in the Devonian Old Red sandstone of Britain and wrote about them in masterly style. His essays, assembled in book form under the title "The Old Red Sandstone" (1841), have led a multitude of readers to better comprehension and increased appreciation of the subject of earth history. In America, we may specially mention James Hall (1811–1898) and John M. Clarke (1857–1925), both of New York and both leading contributors to geologic knowledge, who devoted most of their lives to studies of the Devonian and its fossils. Also noteworthy is the work of the Canadian geologist, Sir William Dawson, who did much in making known the earliest known plant life of the lands, of Devonian age, and in studies of the Devonian rocks of eastern Canada.

Definition of the Devonian.—The Devonian system comprises the rocks that are intermediate in age between the Silurian and the Mississippian, or Lower Carboniferous. The type section of the Devonian is located in the county of Devonshire, in southwestern England. The rocks of this type section contain marine fossils, but in country to the north (Wales, western England, Scotland) some 10,000 feet or more of

red sandstones and shales lie between the Silurian and Carboniferous rocks. These red strata, which are known as the Old Red sandstone, are relatively barren of fossils, but at certain horizons remains of fresh-water fishes and land plants are found.

The lower and upper boundaries of the Devonian are marked in many places by unconformities, but in others, where the strata of successive systems are conformable, the lines of division are assigned on the basis of changes in the nature of the fossil faunas. For example, in Bohemia no physical break between the Silurian and Devonian is evident, and the base of the Devonian is somewhat arbitrarily placed at the horizon where certain fossils of Devonian affinities first appear. The conditions in North America are much the same as in Europe. Unconformities define the limits of the Devonian in most regions, but there is a problem in the Ohio Valley as to the boundary between the Devonian and Mississippian systems.

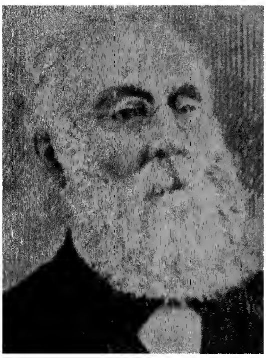


Fig. 133.—James Hall (1811–1898).

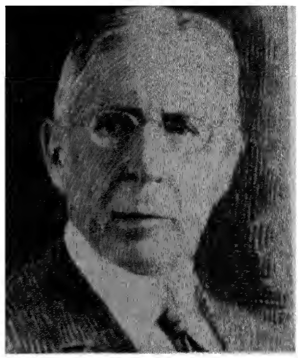


Fig. 134.—John M. Clarke (1857–1925).

GENERAL CHARACTER AND DIVISIONS

Lithologic Features.—Like the older Paleozoic systems, the Devonian contains deposits of conglomerate, sandstone, shale, and limestone.

The conglomerates occur chiefly in the upper part of the Devonian in the Appalachian region. They are mostly part of a great volume of continental sediments (Catskill) that were deposited by streams. Some of the widespread thin conglomerate beds (Chemung) are apparently marine and, in part they may represent beach deposits of advancing or retreating shallow seas.

Sandstone occurs in thick beds and also in very thin, flaggy layers. Some formations consist very largely of sand but others contain only occasional sandy layers. The texture of the sand ranges from very coarse to extremely fine. Reddish sandstone is a prominent constituent of the nonmarine deposits (Catskill) which attain an aggregate thickness of

several thousand feet. An extensive but generally thin sandstone (Oriskany) in the lower part of the Devonian in the Appalachian area is distinguished in many places by the remarkable purity of the quartz sand, which makes it useful for glass manufacture. Sand deposition occurred chiefly in the late part of Devonian time in the Appalachian region.

Shale is a very important type of rock in the Devonian system, especially in the middle and upper parts of the section. The average thickness of shale in parts of the New York and Pennsylvania Devonian is over 7,000 feet. Most of this shale (Hamilton, Portage, Chemung) is bluish-gray and somewhat sandy, but there are large

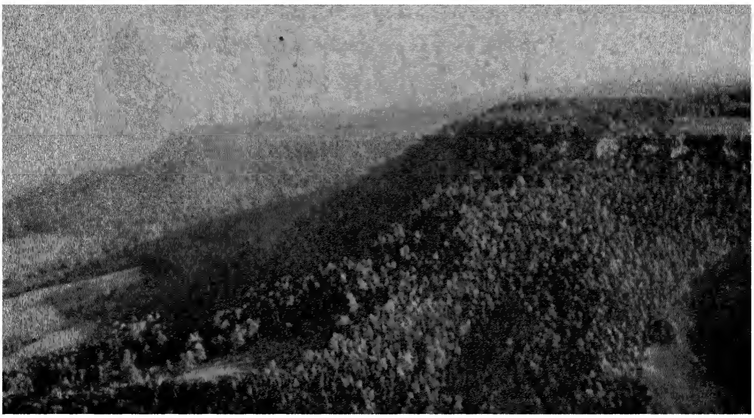


Fig. 135.—The Helderberg escarpment formed by resistant Lower Devonian rocks, near Indian Ladder, N. Y. (*N. H. Darton, U. S. Geol. Survey.*)

amounts of clayey and calcareous shale, and there is much black fissile bituminous shale (Marcellus, Genesee). The shale deposits are almost entirely marine, but there are nonmarine reddish and greenish clay beds (Catskill).

Limestone is not so important quantitatively, or in proportion to other types of sediment, as in some of the older Paleozoic systems, but there are many places, as in Missouri, Iowa, and the Rocky Mountains, where the Devonian deposits consist almost entirely of limestone. Limestones comprise the lower part of the Devonian section in the Mississippi Valley region, where the total thickness of the system is generally less than 300 feet. Limestone is prominent also in the Lower Devonian of the Appalachian region. The Middle Devonian limestone (Onondaga) of New York, which is about 150 feet thick, grades laterally into shales in Pennsylvania. Limestone is the dominant and often the only lithologic element in the lower part of the Devonian section of southern Canada and the Mackenzie River Basin. The limestones vary

widely in composition. Some are dolomitic and almost barren of fossils; others are mostly pure, light-colored, thin-bedded to massive, and very fossiliferous. Chert is abundant in some formations.

Divisions.—The Devonian rocks of North America are commonly divided into three major parts that are designated by the terms Lower, Middle, and Upper. Each of these parts contains a number of formations. The standard Devonian section for North America is that of New York State which offers a practically unbroken record of sedimentation covering the entire period. Indeed, the New York section of this system is one of the best in the world and except for slight priority in publication of the name Devonian we should probably now call these rocks Erian, which was the term used by the early New York geologists.[1] The chief divisions of the Devonian in New York are indicated in the diagrammatic section, Fig. 139. Some of the New York names are commonly used in other parts of North America. Changes in lithologic and faunal characters, however, are responsible for the use of many local formation names, and this is especially true at increasing distances from the New York type section.

The differentiation of the successive series in the Devonian system is based on major changes in the lithologic character of deposits, in the nature of fossil faunas, and in the geographic distribution of the seas and lands. The Lower Devonian rocks differ notably in these respects from the Middle Devonian, and the Middle differs generally from the Upper. In addition, there is evidence in many places of at least a slight unconformity at the major lines of division within the system.

DEVONIAN FORMATIONS OF NORTH AMERICA

Distribution.—Rocks of Devonian age were originally spread throughout the Appalachian region from Newfoundland to Alabama. They covered practically the entire Mississippi Valley, the eastern Great Lakes region, and central Canada, and they were very extensive in the Cordilleran region, the southwestern states, and Alaska. Outcrops of the Devonian rocks are naturally more restricted. There are abundant exposures, however, throughout southern New York; in the Appalachian belt, including eastern Quebec, New Brunswick, eastern Pennsylvania, Maryland, Virginia, and West Virginia; and in parts of Ohio, Kentucky, Indiana, Illinois, Missouri, and Iowa. Devonian limestones appear in the Rocky Mountains from Montana to the Arctic Circle. They are extensively distributed in the Mackenzie Valley of northwestern Canada. A belt of Devonian rocks extends from the Mackenzie region southeastward to the Manitoba Lakes near Winnipeg, and a fairly large area of these beds borders James Bay, at the south tip of Hudson Bay. South of Montana, also, rocks of this age occur in many places as far as Arizona.

[1] The name Erian is now restricted to a subdivision of the Devonian rocks.

The Type Devonian Section in New York

Devonian rocks occupy almost all of southern New York west of the Hudson River, which amounts to about one-third of the area of the state. On the east are the ruggedly beautiful Catskill Mountains, rising to more than 4,000 feet above sea level. These mountains have been carved from a thick mass of nearly flat-lying Devonian rocks capped by the

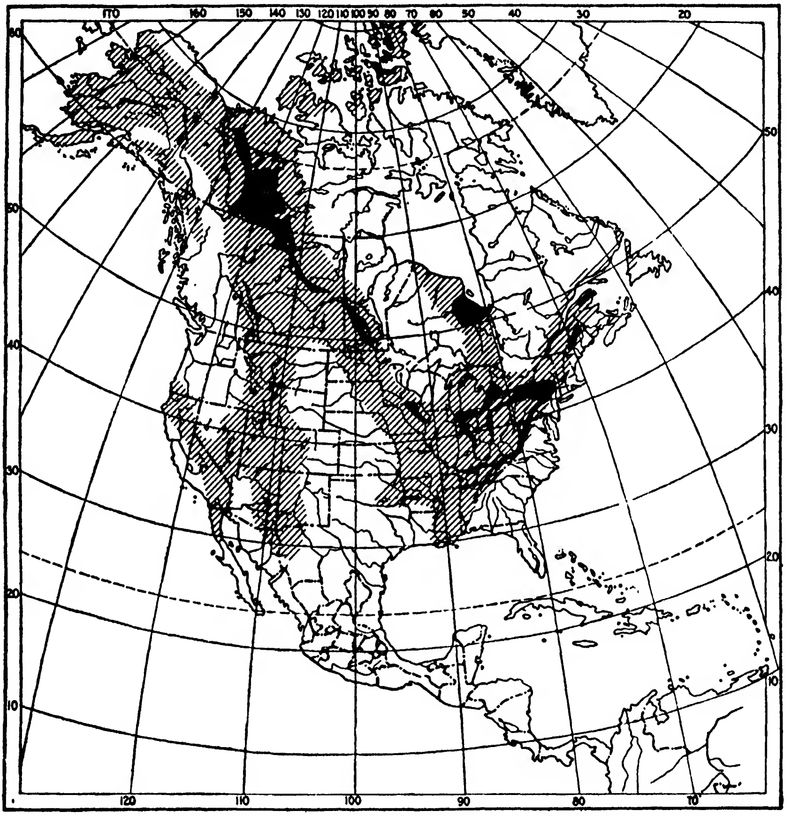


FIG. 136.—Map of North America showing outcrop areas of the Devonian system (black) and the inferred area of original distribution of Devonian formations (oblique shading). (*R. T. Chamberlin, in Chamberlin and Salisbury's Historical Geology, Henry Holt & Company.*)

resistant Catskill formation. Farther west is the intricately dissected upland that forms the northern part of the Allegheny Plateau. The east-west trending outcrops of resistant Devonian formations at the northern margin of the plateau form north-facing escarpments looking down on lowlands made by the weak Upper Silurian shales (Fig. 138). Southwest of Albany is an especially prominent escarpment made by thick Lower Devonian limestones. It is known as the Helderberg Mountains, and from this area the Helderberg series received its name.

Near Lake Erie the exposed Devonian rocks, belonging to the upper part of the system, consist largely of shale and thin sandstone, and the topography is more subdued.

Lower Devonian Formations.—The lowermost deposit of the Devonian system in New York consists of fossiliferous limestone (Coeymans) that rests disconformably on Upper Silurian limestone (Manlius). The complete sequence of the Lower Devonian (Helderberg) beds is found only in the eastern part of the state, whereas none of them occur in the west. The basal limestone extends farther west than the higher forma-

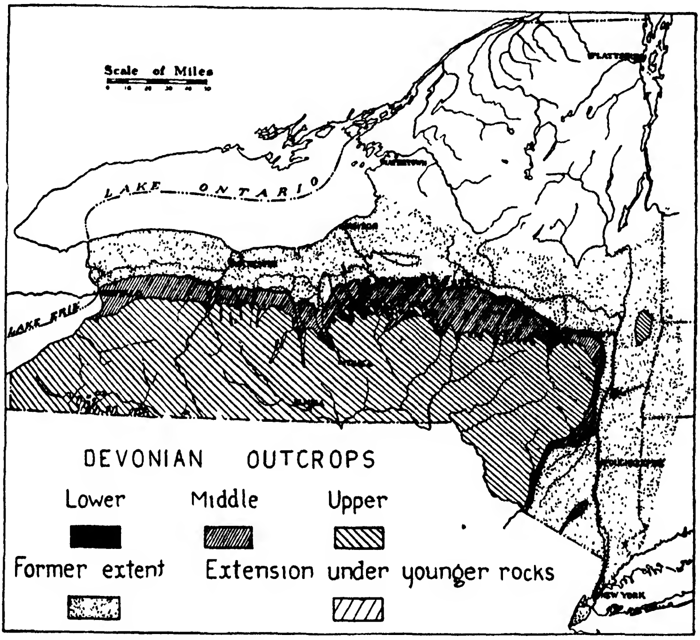


FIG. 137.—Map of New York showing Devonian outcrops. (*Winifred Goldring, New York State Museum.*)

tions, which are progressively restricted toward the east. These relations indicate either that (1) the Helderberg sea reached farthest west in this region during earliest Devonian time and slowly retreated eastward during the later part of the epoch, or (2), if the later Helderberg beds were deposited in areas beyond their present western limits, erosion removed the westerly portions of these beds before deposition of the next younger series. It is possible that the true conditions were a combination of the suggested alternatives.

Parts of the limestone deposits are thick-bedded and resistant to erosion. Some beds contain much chert. Accordingly, these rocks make a prominent escarpment or in places form the tops of high hills. Other parts of the Lower Devonian strata are shaly and relatively weak,

but some of these (New Scotland beds) are especially noteworthy on account of the abundance of their fossils.

The rocks next above the Helderberg series consist of sandstone and some shale (Oriskany) that rests unconformably on older rocks, except possibly in part of eastern New York. The sand overlies successively older Lower Devonian formations from east to west, and in western New York it lies directly on the Silurian. The Oriskany beds contain marine fossils and the observed distribution of these rocks shows that the sea spread westward at least as far as Ontario. The thickness of the deposits in New York is mostly only a few feet.

The Oriskany formation has commonly been classed as belonging to the late part of the Lower Devonian. It is true that many of the fossils in the Oriskany and Helderberg beds are similar, but, on the other hand, many are very unlike. It is clear, also, that the Helderberg rocks were exposed to erosion for some time preceding the deposition of the Oriskany

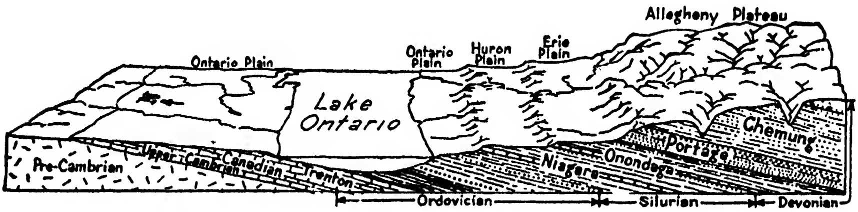


FIG. 138.—Diagram of a part of Ontario and western New York showing topographic expression of the Devonian and older rocks.

strata as shown partly by the distribution of different Helderberg formations and partly by uneven surface and accumulations of residual debris at the base of the Oriskany beds. An interesting feature is the occurrence of fissures in the pre-Oriskany rocks (possibly formed by earthquake shocks) that are filled with Oriskany sand. It is suggested (Grabau) that, during the time of erosion of the Helderberg rocks, sand was spread over the land surface by wind and streams, filling irregularities and accumulating in places as dunes. When the sea readvanced over the New York region, the sand was largely reworked by waves and currents, and marine shells are found in these parts of the deposits. The Oriskany beds are overlaid conformably by the Middle Devonian Onondaga limestone. All these features considered, it is possible that the Oriskany should be regarded as the initial deposit of Medial Devonian time. The series is here classed as Lower Devonian, however, in accordance with general usage.

Middle Devonian Formations.—The Onondaga limestone is a fossiliferous, brachiopod- and coral-bearing formation which is a product of deposition in a clear sea that extended far beyond the borders of New York. It is 200 feet or less in thickness but is fairly resistant to erosion and makes a well-defined north-facing escarpment that is traced from

east to west across the state. Silica in the form of chert nodules is abundant in parts of this formation

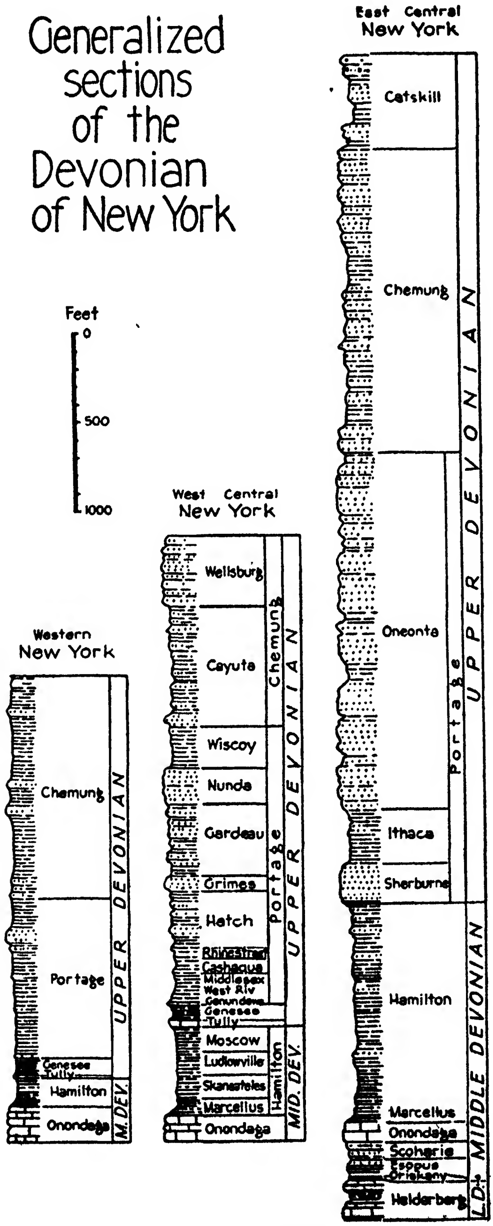


FIG. 139.—Sections of Devonian rocks in New York.

The upper part of the Middle Devonian rocks in New York consists predominantly of shale (Marcellus and Hamilton) about 1,000 feet in

average thickness. The Marcellus shale is a black, bituminous mud deposit that contains a small fauna of diminutive thin-shelled marine animals which indicate a very different sort of environment from that of the lime-depositing seas. The Marcellus is at least partly contemporaneous with the Onondaga limestone, grading into it laterally. The Marcellus formation is thickest in the east where the Onondaga is thin, and it thins to the west where the Onondaga is thick. It has been learned also that the black Marcellus shale grades eastward into gray sandy shale and thin sandstones that lithologically resemble the Hamilton formation.

The Hamilton shale is a bluish-gray silty to fine sandy formation. The eastern New York portion of the Hamilton has greatest thickness and largest content of sand. At the top of the Hamilton formation in eastern New York sections is a thin but persistent conglomeratic sandstone or conglomerate which has recently been traced (Cooper) eastward into the mid-portion of the Catskill beds. This proves that red beds and coarse, irregularly bedded sandstones of continental origin in the lower Catskill formation are of Medial Devonian age, for they are evidently contemporaneous with marine Hamilton beds of areas to the west. Formerly, the Catskill rocks had been regarded as belonging wholly to the Upper Devonian. The Middle Devonian part of the Catskill beds near Gilboa in eastern New York contains successive forest beds with trees 30 to 40 feet high, representing some of the earliest known land vegetation. These old forests indicate a subsiding coast line during the time of their development. The shore line shifted eastward and westward from time to time, as indicated by lateral changes in the nature of the deposits, much of which were derived from the east or southeast. In western New York the Hamilton formation is distinctly thinner than in the east; it contains limestone beds and is entirely marine. These relations indicate that the chief source of the Middle Devonian sediments of this region was a part of the Appalachian borderland to the east of New York. Also, we must now recognize that different formations representing types of deposits (facies) ranging from continental in the east to offshore marine in the west are partly contemporaneous instead of unlike in age.

Upper Devonian Formations.—Shale and sandstone many hundreds of feet thick comprise the Upper Devonian of New York. The base of this division is marked by a thin, nonpersistent limestone (Tully) that contains certain fossils that are characteristic of the Upper Devonian of Europe, and there is evidence that these species reached the New York area by way of the far Northwest. No evidence of an interruption of sedimentation is found in this part of the New York section.

The lower part of the Upper Devonian consists dominantly of marine shale and sandstone. It contains a relatively thin, black bituminous shale (Genesee) at the base, overlain by 1,000 feet or more of grayish shale and sandstone (Portage). The sandy beds are coarsest and thickest

(about 3,000 feet) in the east, becoming fine-grained and thin-bedded to the west; also, part of the eastern deposits contain land plants. The sea reached beyond New York State to the west. Some of the Portage beds in central New York, which by physical characters indicate that they were deposited in very shallow water where wave and current action was

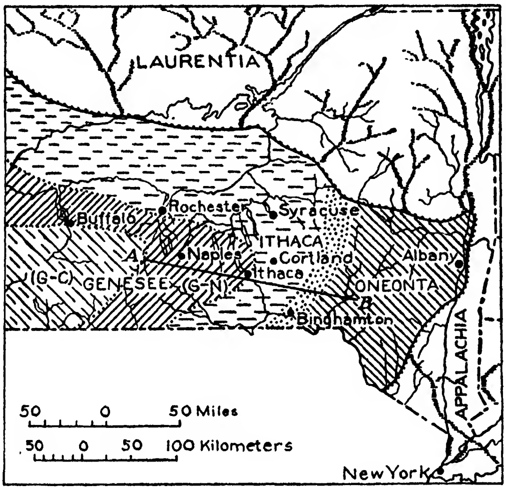


FIG. 140.—Map of the New York region showing distribution of different types of sedimentary deposits and faunas during part of Late Devonian time. The Oneonta facies consisting largely of sandy beds occurs in the east, the Ithaca facies of gray shaly and fine sandy beds in a central belt, and the Genesee facies of black muds containing the Naples fauna in the west. (*From International Geol. Congress Guidebook* 4, *by K. E. Caster, from Clarke.*)

strong, contain coarse, thick-shelled fossils of a type adapted to this sort of environment. It is interesting to observe in beds of equivalent age in western New York, where physical evidence indicates quiet accumulation of fine sediments, that many of the fossils are delicate, thin-shelled types such as are adapted to deeper waters beyond the reach of strong waves

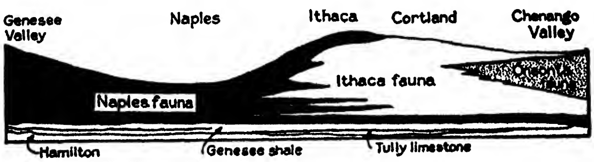


FIG. 141.—Diagrammatic section along the line *A-B* of Fig. 140 showing interrelations of Upper Devonian facies. (*From International Geol. Congress Guidebook* 4, *by K. E. Caster, after Clarke.*)

and currents. There is evidence, thus, in both physical and organic characters, of the geographic conditions of the time.

Eastern New York sections, as shown typically in the Catskill Mountains, show about 1,000 feet of coarse, irregularly bedded reddish sandstone, some conglomerate, and greenish to reddish clay. There are also some nearly white sandstone layers. These resistant rocks, called the

Catskill formation, are partly of Medial Devonian age, as already indicated, and the remainder is of early Late Devonian age. They are really only the lower part of an originally much thicker deposit in this region, for erosion has carried away a great volume of rock that was once present above the existing summits of the Catskill Mountains and has removed all of the Devonian rocks from an area of unknown extent to the east and north of the present Devonian outcrops. The physical properties of this formation, including irregular stratification, cross-bedding, and mud cracks, and the presence of land plant and fresh-water animal remains, indicate clearly that the deposit is of nonmarine origin.

The upper Upper Devonian beds of western New York consist of fossiliferous shales, thin sandstones, and limestones that are entirely marine. These beds are known as the Chemung formation. Farther east, the upper part of the Chemung beds is replaced by deposits of Catskill type; farther on, the middle Chemung also grades laterally into Catskill; and still farther the lower Chemung is changed to continental materials. It is evident that the Catskill and Chemung beds of New York are partly contemporaneous deposits of different character, though the Catskill formation includes beds that are much older than the lowest Chemung. One was laid down on land by streams and in lakes, or in part as lagoonal deposits bordering the coast line, and the other was formed in the adjacent shallow sea. Also, as time in the Late Devonian epoch elapsed, the land was built farther and farther westward, restricting the area of marine sedimentation correspondingly. Minor oscillations of the shore line are shown by the occurrence of tonguelike extensions of the nonmarine beds into the marine and of marine beds into the nonmarine. These interbedded relations are readily understood, for, if outbuilding of land deposits is followed by submergence of a near-shore area, owing to either sinking of the deposits or a slight rise of the sea, marine sediments come to rest on nonmarine; and as the near-shore portion of the shallow sea is filled in and land deposits are built seaward, nonmarine strata come to overlie marine beds. This sort of change, with alternating temporary mastery of sea and of land in the zone where they meet, is to be expected, but in the case of the Late Devonian in New York the land greatly outgained the sea.

The Appalachian Region

The Devonian rocks of the Appalachian region are steeply folded and faulted, like the older systems. Accordingly, the outcrops occur in long bands whose width is determined mainly by the thickness of the rocks and the angle of dip. There are good exposures in many places, especially where streams cut through the mountain ridges, and because of the steeply tilted attitude of the beds it is possible in a walk of one or two miles to cross outcrops representing a thickness of thousands of feet. The greatest

thickness of Devonian rocks in North America is found in east central Pennsylvania where measurements show a total of 13,000 feet for the system. About two-thirds of this thickness belongs to the Upper Devonian. There is a regular decrease in thickness westward, and also northward and southward along the axis of the trough.

The Lower Devonian formations, consisting of limestone (Helderberg) in the lower part and of sandstone and cherty limestone (Oriskany) in the upper part, are essentially the same as rocks of this age in New York. They are continuous southwestward into Alabama, the total thickness ranging to nearly 1,000 feet in some places.

Middle Devonian deposits of the Appalachian trough consist almost entirely of shales. These rocks attain a total thickness of about 1,600

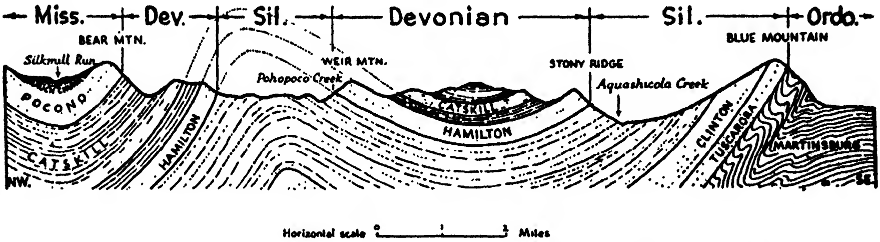


FIG. 142.—Geologic section of Devonian and associated rocks in part of southeastern Pennsylvania. (*From International Geol. Congress Guidebook 7, by D. W. Johnson.*)

feet in Pennsylvania. They thin southward, disappearing in Virginia. As in New York, the lower part of the Catskill formation is apparently of Medial Devonian age.

The Upper Devonian rocks of this district are very similar to those of New York. The lower part consists of marine shale and sandstone, in the east representing only the very early Late Devonian, but farther west including all of this division. The upper part consists of continental sediments of the Catskill red-beds type in the east, grading into and interfingering westward with marine deposits of the Chemung type. The maximum thickness of Catskill nonmarine beds is about 7,500 feet in northeastern Pennsylvania. The thickness decreases southwestward along the outcrop until the beds disappear near the Virginia-Tennessee boundary. The distribution of thickness and coarseness of the Catskill sediments offers basis for the inference that the chief aggrading streams of this Late Devonian piedmont alluvial fan were located in the Pennsylvania portion of the Appalachian belt. The headwaters of the streams were located in highlands or mountains of Appalachia lying probably 100 miles or more east and southeast of the site of Philadelphia.

Eastern Canada and New England

Devonian rocks occur in southeastern Quebec, northern and southern New Brunswick, Nova Scotia, and Maine. The best-known and prob-

ably the most interesting Devonian section of this region is that of the picturesque Gaspé Peninsula in eastern Quebec, on the south side of the Gulf of St. Lawrence. Here the Lower Devonian (and in part the Middle Devonian) is represented by some 2,000 feet of fossiliferous sandstones, limestones, and shales, overlaid unconformably by a mass of Catskill-like reddish and irregularly bedded conglomeratic sandstones and shales 1,000 feet or more in thickness. The rocks of Catskill type above the unconformity are now thought to be of Carboniferous age rather than Late Devonian. The marine beds of the Gaspé Devonian are interbedded with volcanic flows and beds of conglomerate are present in the western Gaspé sections. Similarity of fossils strongly suggests that the Lower Devonian sea of the Gaspé region was directly connected with that of the Appalachian trough in eastern New York and farther south. If this is the case, erosion removed Devonian deposits that were once present in the several hundred miles that now separate the nearest exposures of corresponding beds. The thick nonmarine strata of the eastern Quebec and northeastern New Brunswick district show evidence of deposition by streams coming from a highland area southeast of this region. The remains of land plants and of fresh-water fishes characterize earliest and latest beds of this series.

The Devonian formations of southern New Brunswick, Nova Scotia, and Maine are sandstones and shales, that are complexly folded, faulted, and partially metamorphosed. Only Lower Devonian beds are recognized in Nova Scotia. There is much igneous rock, both extrusive materials and intrusive masses. Among the latter are granitic batholiths, probably including that of the White Mountains in New Hampshire.

The Continental Interior

The Devonian of the Continental Interior consists mainly of the westward continuation of certain formations of the New York and Appalachian region. In addition, there are deposits of seas that invaded from the south and from the northwest that are independent of the eastern seaways. The deposits of the Continental Interior are distinguished chiefly by very moderate thickness and in areas west of Ohio by dominance of limestone. The Devonian beds lie on Upper, Middle, or Lower Silurian, on Ordovician, or locally even on Cambrian, yet the parallel position of the beds and the generally very even contact at the base of the Devonian give appearance of conformity.

Lower Devonian formations consisting chiefly of limestone occur in western Tennessee, southern Illinois, southeastern Missouri, and southern Oklahoma. The thickness is mostly less than 100 feet. Some of the formations are especially characterized by abundance of chert, and some contain fossils that are beautifully preserved and very abundant. The total area of these beds is small. Evidence from fossils indicates that

the sea of the interior region was connected at this time with the Appalachian trough and probably also with waters at the continental margin in the south.

The Middle Devonian is widespread in the Ohio Valley and Great Lakes region, upper Middle Devonian being found also in Missouri, Iowa, and western Canada. The deposits consist almost entirely of limestone that corresponds to the Onondaga and Hamilton formations of New York. The limestone of this age in western Tennessee is extremely cherty, and in the Ouachita Mountain region of Arkansas there are thick beds of silica (in the massive, even-textured form called *novaculite*) without any limestone. The average thickness of Middle Devonian rocks of the

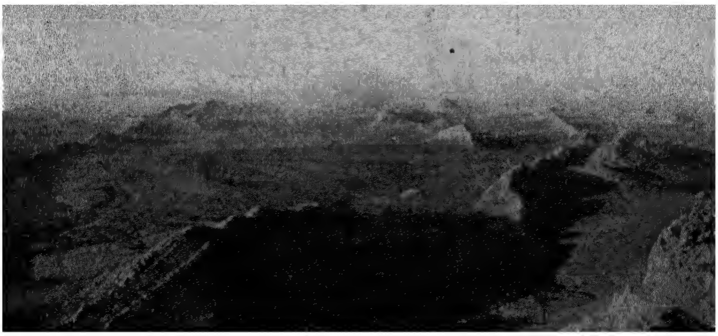


FIG. 143.—Ridges of Devonian siliceous rock (novaculite) in the Marathon Uplift of western Texas. These rocks were folded in Late Pennsylvanian time. (*From International Geol. Congress Guidebook* 13. *Photograph by P. B. King, U. S. Geol. Survey.*)

interior region is about 100 feet. An interesting feature of these beds in several places is the occurrence of large coral reefs. A famous locality for collection of Middle Devonian fossil corals is the so-called Falls of the Ohio near Louisville, Ky., the "falls" (now removed by river improvements) being due to a partly silicified reef that chanced to lie in the river's path. More than two hundred species of corals have been obtained from this place. Port Colborne, at the south end of the Welland ship canal, Ontario, is another famous locality for Onondaga corals. The Middle Devonian also contains "bone beds" that are made up almost wholly of the teeth, plates, spines, and other skeletal fragments of millions of fishes. One such bed, a few inches thick, can be traced in a north-south direction almost across the state of Ohio.

The Upper Devonian rocks of the Continental Interior consist of shale and shaly limestone. The Ohio Valley and Michigan region contain dark-colored shale, 100 to 500 feet or more thick, some holding many large rounded concretions, and some that is black, yielding oil on distillation. The shales are not very fossiliferous and the fossils of certain beds indicate an environment of brackish or stagnant waters that is very

unlike the normal marine shallow seas. An important feature of the Upper Devonian is the presence of beds extending to the far northwest in the Mackenzie Valley region of Canada. The sea that occupied this territory invaded from the Arctic and spread through the Mississippi Valley to New York. Some of the fossils in deposits of this sea can be distinguished as Asiatic or European in origin.

The Cordilleran Region

Devonian rocks are known in Arizona, Colorado, Utah, Nevada, Wyoming, Idaho, and Montana. The thickest section appears in Nevada where at least 6,000 feet of beds, mostly limestone, is reported. Most of the western Devonian belongs to the middle and upper parts of the system, but all of the divisions are represented in Nevada.

DEVONIAN FORMATIONS OF OTHER CONTINENTS

Europe.—The great chain of mountains that was formed at the close of Silurian time in northwestern Europe was the source of huge quantities of gravel, sand, and finer sediments which now compose the thick nonmarine Old Red sandstone of Great Britain and other parts of northern Europe. These deposits are very much like those of the Upper Devonian Catskill beds in America, but in places there are boulders up to 8 feet in diameter, and the total thickness of the Old Red sandstone (at least 20,000 feet in places) is much greater than that of the Catskill formation. A part of these deposits in Europe appears to be an accumulation of rock waste in intermontane basins. It is probable that there were recurrent uplifts during Devonian time of the mountainous highlands that supplied the sediments and there was certainly a great deal of igneous activity in Scotland, Scandinavia, and adjacent areas that was contemporaneous with Old Red sedimentation. The Old Red sandstone is very prominent in Wales, western England, and Scotland and is one of the best-known geological formations in Europe.

Marine deposits of Devonian age occur in southwestern England where the system was named. They consist of sparsely fossil-bearing thick shales and sandstones that are complexly folded and faulted and intruded by igneous rocks. Marine strata with many well-preserved fossils are found in the lower Rhine region of Germany, in France, and in various other parts of western and southern Europe. The Devonian is also widespread in Russia.

Other Continents.—Devonian rocks occur in central Asia and China, southern Asia, southern Africa, Australia, New Zealand, and South America. One of the most common Upper Devonian index fossils of Europe and America can be purchased in the medicine shops of China. The Devonian of southwestern Australia, consisting of shales, sandstones, and much volcanic rock, has a total thickness of about 24,000 feet.

PHYSICAL HISTORY OF DEVONIAN TIME

Early Devonian Time.—At the beginning of Devonian time the Appalachian trough was occupied by an arm of the sea that had persisted from the late part of the Silurian period. Limestone was deposited in this sea. Early Devonian seas, likewise recorded by limestone, also submerged parts of Oklahoma, Tennessee, Missouri, and Illinois, and

fossils indicate that there was a marine connection between this region and the Appalachian trough.

The comparatively small portion of North America submerged in Early Devonian time corresponds to conditions of the ideal cycle in a geologic period, which begins with moderate marine invasion, is followed by very extensive submergence of the lands, and closes with receding seas. It is unusual, however, to find the initial deposits of a geologic system composed of limestone, because emergent lands and restricted seas provide conditions that are normally favorable for deposition of gravelly, sandy, or at least clayey sediments derived from the lands. The limestone formations of the lowermost Devonian emphasize the conclu-

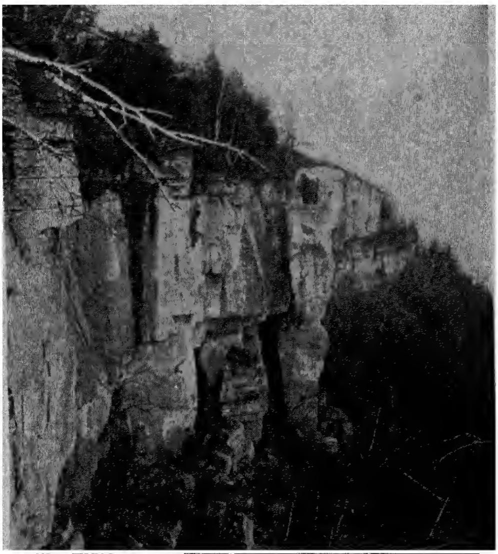


Fig. 144.—Lower Devonian limestone (Coeymans) in the Helderberg escarpment southwest of Albany, N. Y. (*N. H. Darton, U. S. Geol. Survey.*)

sion that the land surface of North America, even though very large at this time, was so little above sea level (and possibly so covered by vegetation) that no appreciable amounts of detrital sediments were transported to the seas.

Local changes involving partial retreat of the Devonian sea are recorded by the presence of a hiatus, well shown in New York, between the Helderberg and Oriskany series. The readvance of the sea in Oriskany time is mainly registered by sandstone deposits that overlap the older formations. The deposition of sandstone is in itself an indication of a significant change in physiographic conditions, for sand is virtually lacking in the Helderberg beds. The sandstone of the Oriskany series may mean the uplift of a near-by land area containing sand or sandstone, erosion of the sand, and transportation of it to the sea. The

purity and the well-rounded shape of the Oriskany sand grains are characters resulting from thorough sorting and considerable wear. They imply that this Devonian sandstone was derived from the erosion of preexisting sand deposits rather than from the disintegration of granitic or other quartz-containing crystalline rocks, for in these latter there is much nonquartzose material to be sorted out and deposited somewhere. It is probable that the sand was spread over parts of the Appalachian region by wind and streams during the time of erosion in the late Early Devonian epoch, being reworked by the sea in the course of the marine transgression that possibly should be reckoned to define the beginning of Medial Devonian time. Limestone beds were deposited also in Oriskany time. The fossils of this epoch are partly descendants of Helderberg species but there are also immigrant types so similar to Early Devonian species from South America that they are considered to have come from this region, probably by way of the west shore of the Atlantic.

Medial Devonian Time.—The chief event of Medial Devonian time is the greatly increased submergence of North America. In the Onondaga stage the sea occupied almost all of the eastern Mississippi Valley region, the northern part of the Appalachian trough, and east central Canada at least as far north as Hudson Bay. In the west, the sea was present in the Cordilleran region. The chief type of deposit was limestone. The limestone contains especially abundant corals and in some regions there are coral reefs. The new elements in the invertebrate life of Onondaga seas appear to have come from the north; they are not known in South America.

The later part of Medial Devonian time is that in which the Hamilton beds and their equivalents were deposited. The physical character and thickness of these shaly and sandy sediments in the eastern United States give evidence of gradual elevation of the borderland east of the Appalachian trough, as has been indicated in previous discussion, but limestone was deposited in the Mississippi Valley and Great Lakes region at a distance from Appalachia. The eastern Hamilton deposits contain several distinctive immigrant fossils that came from South America, and therefore the Hamilton sea evidently had a southern connection.

Contemporaneous with the Hamilton marine invasion in the east, there was a great extension of a sea that advanced from the northwest, bringing shallow-water organisms characteristic of the European and Asiatic regions. This sea covered a large part of western Canada, the western and southwestern United States, and it reached eastward to Iowa and northern Illinois. It was prevented from uniting with the Hamilton sea farther east by a low barrier of land in eastern Illinois and adjacent territory (Kankakee axis). The evidence of these late Medial Devonian geographic conditions consists in the distribution of the rock formations of this age and especially in the nature of their fossils.

Elevation of Appalachia in late Medial Devonian time resulted in formation of a highland or mountainous area and led to greatly increased erosion of the land and the transportation westward from it of an enormous quantity of detrital materials consisting of gravel, sand, silt, and clay. These sediments comprise the great thickness of stratified rocks in the Catskill, Hamilton, and younger Devonian formations of the Appalachian region. An unknown but certainly large part of the original deposits has been destroyed by post-Devonian erosion. This applies to the former northward continuation of the Upper Devonian formations in New York, but especially to the territory between the present easternmost outcrops and the original eastern limits of the deposits in the foothills of Appalachia. In considering both the existing remnants of the formations and probable characters of the vanished portions, it is practically certain that deposition of nonmarine beds at the borders of the upland and of marine beds at greater distance from the upland took place in the Appalachian region throughout late Medial and all of succeeding Devonian time.

Late Devonian Time.—During the Late Devonian epoch, conditions were very similar to those of Hamilton time, although sedimentation of continental type extended gradually and intermittently farther to the west. The Genesee black muds were deposited in the west while sandy shale, sandstone, and continental beds were being formed in the east. The black muds were succeeded by sandy shale and sandstone of the Portage beds, the latter containing most sandstone and some nonmarine strata toward the east. The western sea which in late Medial Devonian time had extended eastward only to Illinois advanced beyond the barrier that had prevented a connection with the eastern sea, and at the beginning of the Late Devonian there was a continuous marine area from New York to the lower Mackenzie Valley and to the Cordilleran and Southwestern regions of the United States.

The Late Devonian epoch is characterized by the great accumulation of coarse continental deposits that form the upper Catskill beds, and the gradual westward restriction of the sea and enlargement of the land through building of a wide piedmont fan. The surface of this fan was a gently sloping plain that extended from the border of the Devonian highlands in Appalachia to the shore of the interior sea. At its maximum stage of development near the close of Devonian time, the Catskill piedmont plain was probably not less than 200 miles wide and it extended at least 500 miles along the western edge of Appalachia. The central part of the plain, and the region of thickest continental sedimentation, was in eastern Pennsylvania. Another fan, possibly connected originally with that of the Pennsylvania region, was formed in the region south of the Gulf of St. Lawrence. The fact that the continental deposits came gradually to extend farther and farther west shows that downward sinking of

the Appalachian geosyncline did not keep pace with the rate of sedimentation. Accordingly, the sea was filled in and stream deposits were spread out to increasing distances beyond the original shore at the west edge of Appalachia.

The youngest marine deposits of Late Devonian age, that is, the Chemung beds of New York and adjacent states, are most sandy in the east and they grade westward into fine dark shale of the Ohio Valley region. These conditions are a result of the physical geography of Late Devonian time.

Climate.—Evidence of climatic conditions in Devonian time lies in physical characters of the formations and the nature of the fossils. The low lands and widespread limestone deposits imply general uniformity of climate during the early and middle parts of the period. Corals which are abundant in the limestones of the eastern United States and also of Arctic regions suggest at least moderate warmth.

The reddish nonmarine sediments of Medial and Late Devonian age, which are so prominent in the Appalachian region and in northern Europe, have been interpreted as evidence of aridity. As noted previously, red color does not of itself prove extreme dryness. For example, yellowish-brown sediments in which the color is due to hydrous iron oxide may become red through loss of the combined water. Stream deposits of regions that are alternately wet and dry are commonly of this character. The physical nature of the Devonian continental sediments suggests a variable climate with times of considerable rainfall, of periodic dryness, and of moderate warmth. The similarity of the land plants of the Upper Devonian beds in eastern North America, the Arctic region, and Europe suggest an absence of great geographic variation in the later Devonian climates, but the presence of annual rings in fossil woods from Devonian black shale of Kentucky and Indiana points to the existence of fluctuations.

Close of the Period.—The end of Devonian time is marked in North America by geographic changes involving general withdrawal of the seas from the continent, by at least local crustal disturbances, and by changes in the faunas.

The earth movements, accompanied by considerable igneous activity, are commonly designated as the *Acadian disturbance,* for the most pronounced structural deformation of Devonian rocks and the most important igneous activity are centered in the eastern Canadian country. Strong elevation of northern Appalachia began in Medial Devonian time, and there were similar disturbances of this borderland farther south, forming the so-called Devonian Highlands. It is probable that a considerable range of mountains were made. Erosion of this highland or mountainous region furnished the materials of the Devonian land deposits of the Catskill type and also of part of the contemporaneous marine for-

mations. The Devonian stratified rocks of the Acadian region, including some of the very late Devonian, were strongly folded. Igneous intrusion is marked by volcanic plugs or necks, near Montreal and elsewhere, and by granitic batholiths. It is noteworthy that the earth movements belong to the middle and latter parts of Devonian time rather than the end of the period. They were apparently spread over a long time and they greatly affected sedimentation in the eastern part of North America in the Devonian period. Much of the vulcanism is of late Early and Medial Devonian age.

On the east side of the Ozarks in southeastern Missouri there was Late Devonian faulting in which the rocks were displaced at least 1,000 feet, but there was no folding of the strata. Topographic inequalities produced by the faulting were obliterated by erosion before Early Mississippian time, for marine beds of the latter age extend evenly across the fault lines, covering Devonian on one side and Lower Ordovician on the other.

A great range of mountains were formed in eastern Australia at the close of Devonian time.

In contrast with the disturbances described, it should be noted that throughout most of North America the Devonian and succeeding rocks lie parallel. A disconformity marks the boundary between Devonian and Mississippian strata in many places, but in others there is difficulty in determining the intersystemic boundary.

ECONOMIC PRODUCTS

The chief materials of economic importance in the Devonian rocks of North America are oil and gas. These are found in largest quantities in the so-called Appalachian fields comprising parts of southern New York, western Pennsylvania, and West Virginia. The oil is one of the best grades, selling at prices that are considerably above average. It occurs in porous sands and fine conglomeratic beds of the Upper Devonian, and also in part of the overlying Mississippian beds of this region. There is a large quantity of natural gas, also (chiefly from the Oriskany sandstone), which is especially valuable because of nearness to large population centers. Middle Devonian limestone is one of the most important oil-producing horizons in Kentucky and oil is found in the Lower Devonian limestone of Oklahoma. A test well secured a good flow of oil near the base of the Upper Devonian in the Mackenzie River Valley about 1,000 miles north of railroad transportation. The Upper Devonian black shale of Indiana and Ohio contains oil that may be commercially valuable in the future.

Glass sand occurs in the Oriskany beds of the Appalachian region from Virginia to the Gaspé Peninsula in Canada. Moderately thin and evenly bedded hard sandstone or limestone of Devonian age has been extensively quarried for use in building and paving (flagstone). Black phosphate-bearing shaly beds, useful as a fertilizer, occur in the Upper Devonian of Tennessee. Novaculite, which is a very fine, even-textured variety of chert used in making grinding stones, is the most prominent constituent of the Devonian deposits in central Arkansas. In addition, Devonian rocks are much used as a source of stone and of cement manufacture in New York, Ohio, Indiana, Ontario, and other parts of the continent.

SUMMARY

The Devonian formations consist of extensive marine beds, chiefly limestone and shale, and of unusually thick, locally prominent nonmarine red-beds deposits. The marine formations are noteworthy for the abundance, variety, and excellent preservation of fossils in many places. The nonmarine rocks, though generally unfossiliferous, contain the oldest known land flora, several sorts of fishes, and the first evidence of land vertebrates.

The Devonian rocks are bounded below and above in most places by unconformities. The system is commonly divided into three parts, called Lower, Middle, and Upper.

The chief outcrops of Devonian beds occur in the Appalachian region, the eastern Mississippi Valley and Great Lakes area, and in the Mackenzie Basin of northwestern Canada. Additional widely scattered exposures show that at one time or another, chiefly in the middle portion of the period, the seas covered a large part of the continent.

The best Devonian section in North America is that of New York State, for the succession of deposits is essentially complete, the formations contain abundant fossils, and there are excellent exposures. The lateral gradation and interstratification of marine and continental deposits are also well-shown. Accordingly, the most widely used names in the Devonian stratigraphy of this continent come from New York.

The Lower Devonian, which is best developed in the Appalachian district, consists typically of limestone (Helderberg), and a pure quartz sandstone and cherty limestone (Oriskany).

The beds classed as Middle Devonian contain at the base limestone beds (Onondaga) in New York, the eastern Mississippi Valley and south central Canada. These strata are followed by thick shaly deposits (Hamilton) that grade eastward into sandy beds and continental deposits (lower Catskill) and westward into calcareous beds. Middle Devonian strata cover a large territory in the western and southwestern parts of the continent.

Upper Devonian deposits of the Appalachian area consist of thick marine shaly and sandy beds (Genesee, Portage, Chemung) in the west and of continental deposits (Catskill) in the east. The latter represent a great piedmont fan that was spread out westward from a highland region of Appalachia.

The elevation of Appalachia, accompanied by folding of Devonian deposits in eastern Canada and by extrusion and intrusion of igneous rocks in this region and New England, is called the Acadian disturbance. It began in Medial Devonian time and culminated in the late part of the period.

CHAPTER XVII

FORMATIONS AND PHYSICAL HISTORY OF MISSISSIPPIAN TIME

The rocks called Mississippian are equivalent to the lower part of the Carboniferous system of common European classification, and the Pennsylvanian rocks correspond to the upper part of the Carboniferous. The consensus of judgment among American geologists increasingly supports the view that the Mississippian and Pennsylvanian deposits should be reckoned as independent geologic systems rather than as subordinate divisions (series) of a so-called system that combines them. The essential reasons for this view are found (1) in the occurrence almost everywhere of an important unconformity between the Mississippian and Pennsylvanian rocks, and this is true of equivalent strata in Europe, (2) in broadly contrasting conditions of sedimentation and resultant lithologic differences of the two divisions, and (3) in paleontologic distinctions. These evidences will be examined subsequently. It may be remarked that the length of geologic time represented by the Mississippian is apparently greater than that of a number of other recognized periods, and that the Pennsylvanian is probably half again as long as the Mississippian. Excellent type sections of these systems are found in the Mid-Continent region of North America. They are fitted to serve as a standard for comparison with deposits of similar age in other continents, and it is possible that the names Mississippian and Pennsylvanian may be accepted ultimately with world-wide application.

The latter part of Paleozoic time was marked by a tendency of the continental areas to change from generally submergent to broadly emergent conditions. The Mississippian formations, like those of older Paleozoic systems, are dominantly marine. The Pennsylvanian rocks contain a large proportion of continental sediments and show a remarkable succession of alternating marine and nonmarine strata, indicating that the average surface of sedimentation was close to sea level. The Permian system contains a still greater proportion of beds of the continental type. Accompanying the higher average stand of the continents in Late Paleozoic time there was mountain-building in many parts of the world.

Definition of Mississippian.—The Mississippian rocks were named from exposures in the bluffs of the Mississippi River in Iowa, Illinois, and Missouri. These exposures show a nearly unbroken sequence of highly fossiliferous strata that serve to define clearly the important character-

istics of the system and to mark the chief stratigraphic divisions that are applicable to other regions. The Mississippi River section of Mississippian rocks corresponds for this system, therefore, to the New York section of Devonian rocks for the Devonian.

The base of the Mississippian is marked in the type region by an easily recognized unconformity, for the initial Mississippian beds are found in different places to rest on Middle and Lower Devonian formations, on Silurian, and on several Ordovician formations. This implies that erosion prior to the beginning of Mississippian sedimentation removed varying amounts of older rocks, but it does not necessarily mean that all of the erosion belongs to the interval separating time of

FIG. 145.—Middle Mississippian limestone (St. Joe) resting disconformably on Lower Ordovician dolomite (Cotter) near Reeds Spring, southwestern Missouri. (*R. C. Moore, Missouri Bur. Geol. and Mines.*)

deposition of the latest Devonian beds of the region from that of the earliest Mississippian beds. If the Mississippian sea covered territory that was not submerged in Devonian time, sediments would there be laid on rocks that had been subject to erosion since Silurian or even earlier time. In any case, the lower limit of the Mississippian system in most areas is well established.

There are some regions, however, where it is difficult to draw a line between Devonian and Mississippian deposits. This difficulty is naturally found where sedimentation, either marine or nonmarine, was uninterrupted from one period to the next. No case of continuous marine sedimentation from Devonian into Mississippian time is definitely known in North America, but such continuity may be assumed to exist at least on parts of the continental margins and in the ocean basins. Continental sedimentation which was prominent in the Appalachian region in Late Devonian time continued into the Early Mississippian. The lower part of the deposits here is undoubtedly Devonian, while the upper, which is not clearly separable from the lower, is Mississippian. The Ohio Valley contains a succession of dark-gray, black, and some

reddish shale that is mostly very poor in fossils, but some of the beds can be identified definitely as Devonian. Shale in the upper part of this section, however, contains fossils and shows lithologic characters that are identical with deposits at the base of the Mississippian system where it unconformably overlies various older Paleozoic beds. The division of the Devonian and Mississippian portions of the shale in the Ohio Valley region is therefore not settled definitely.

The upper boundary of the Mississippian rocks is marked almost everywhere by a prominent unconformity, the characteristics of which will be described in the following chapter. In both North America and Europe, rocks of Mississippian age were folded and faulted in certain regions before the beginning of Pennsylvanian sedimentation, but in most places the bedding planes of the two systems are essentially parallel.

General Character.—In both North America and Europe there are two broadly contrasting types of Mississippian marine deposits, the one consisting chiefly of limestone and the other composed of dark shaly and fine sandy sediments with little or no limestone. A third type includes the reddish and dark-colored nonmarine formations that occur in some regions.

The most characteristic kind of rock in the Mississippian section of the Mississippi Valley and western states is limestone. The nature of the limestone varies considerably but the lithologic features of each formation or stratigraphic horizon are fairly constant. The chief varieties are an exceedingly fine-grained, dense, bluish limestone; a medium- to very coarse-textured, crystalline limestone composed largely of crinoid fragments; and oolitic limestone. Chert is exceedingly abundant in some formations, occurring in large ellipsoidal masses, small irregularly shaped nodules, and continuous beds. It is interesting to observe that the chert of different Mississippian formations can be differentiated in many instances by peculiarities of form and texture, and that the Mississippian chert is distinguishable in many cases from chert derived from underlying Ordovician and Upper Cambrian (Ozarkian) strata. The thickness of Mississippian limestone in continuous section, that is, with practically no interbedded shale or sandstone exceeds 1,000 feet in some places.

The so-called "Carboniferous limestone" of continental Europe, which is of Mississippian age, is very prominent in many places. Its reported thickness in Ireland and part of England is as much as 3,000 feet. The limestone grades laterally into shaly and sandy beds.

The Mississippian deposits of some regions consist almost entirely of shale and sandstone. This applies especially to the Appalachian and Ohio Valley regions in the United States, and in Europe it distinguishes the beds called Culm. The shaly formations are mostly very dark-gray or black. The sandstones are commonly fine-grained and in many places

are interbedded with shale. Some of these deposits are marine, containing a distinctive assemblage of invertebrates adapted to a muddy sea bottom, but some are apparently nonmarine, for the only fossils are the remains of land plants. The thickness of Mississippian shale and sandstone beds (Stanley) in the Ouachita Mountains region of Arkansas and southeastern Oklahoma is at least 6,000 feet, and it is more than twice this amount if an overlying succession of sandstones (Jackfork), of debatable Late Mississippian or Early Pennsylvanian age, belongs to the Mississippian.

Red shale and sandstone (Mauch Chunk) with a maximum thickness of about 3,000 feet form the upper part of the Mississippian system in much of the Appalachian region, and there are deposits of this type also lower in the Mississippian. They are evidently of nonmarine origin. There are workable coal beds in a few of the Mississippian continental formations (in Bland and Pulaski counties, Virginia, and the Donetz Basin, Russia).

MISSISSIPPIAN FORMATIONS OF NORTH AMERICA

Distribution.—Rocks of Mississippian age occur throughout much of the Mississippi Valley; the Appalachian Mountains and Plateau region; the western United States, Canada, and Alaska; and in eastern Canada. The total area covered by the sea at some time during this period is about equivalent to that of Devonian time, but the distribution of the submerged territory is somewhat different. Study of the important characters of the Mississippian formations of North America may be arranged advantageously according to the following outcrop areas: (1) the type region, including parts of Iowa, Illinois, and Missouri; (2) the lower Ohio Valley, including parts of Indiana, Kentucky, Tennessee, and Alabama; (3) the Appalachian Mountains and Plateau area, including parts of Pennsylvania, Ohio, Kentucky, West Virginia, Virginia, Maryland, Tennessee, and Alabama; (4) the Michigan Basin; (5) the Mid-Continent region, including parts of Missouri, Kansas, Oklahoma, Arkansas, and Texas; (6) the western United States and Canada; and (7) the maritime provinces of eastern Canada.

Classification.—The Mississippian, like all other geologic systems, especially those that are very widespread and composed of varied deposits with differing fossil content, includes a large number of formations, some of which are fairly extensive and easily recognized, whereas others are only local deposits. The classification of the rocks of the type region should be applicable in major features at least to other areas, but because the Mississippi River section consists almost entirely of marine limestones there has been difficulty in establishing its exact relationships to distant geologic sections composed mostly of clastic sediments, especially to those that consist mainly of nonmarine beds. There has been a good

deal of variation in classification of the Mississippian rocks, but according to present knowledge there is no real basis for some of the groupings that have been proposed. We shall here recognize three main divisions of the Mississippian system, each with broadly distinguishing lithologic and faunal characteristics, each marking a major change in the general distribution of sea and land, and each delimited more or less definitely by unconformities. These are the Lower Mississippian or Kinderhook

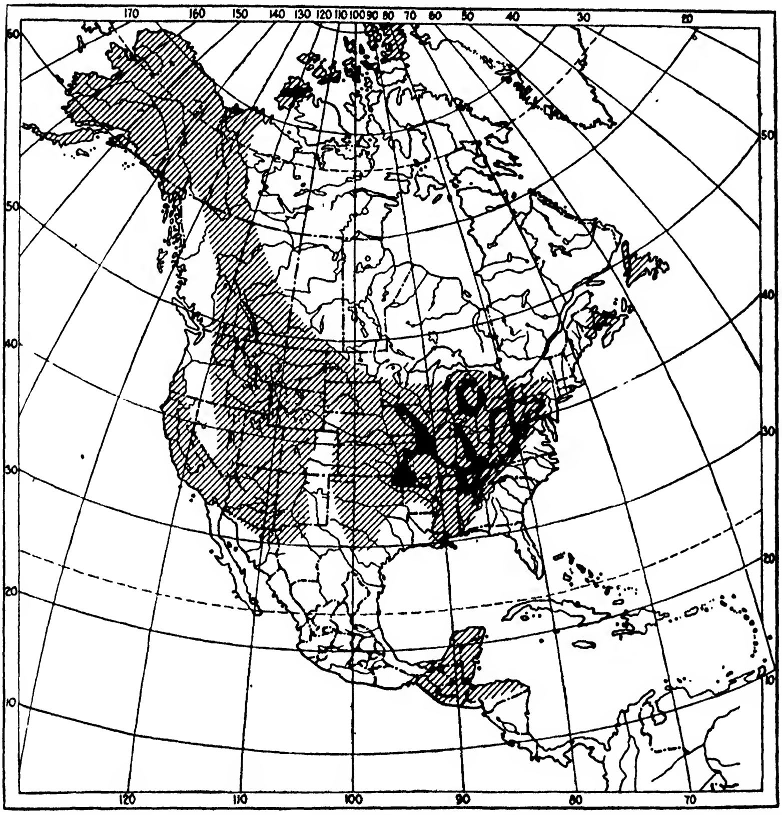


FIG. 146.—Map of North America showing outcrop areas of the Mississippian system (black) and the inferred area of original distribution of Mississippian formations. (*J. M. Weller, in Chamberlin and Salisbury's Historical Geology, Henry Holt & Company.*)

series, the Middle Mississippian or Valmeyer series,[1] and the Upper Mississippian or Chester series.

The Type Mississippian Section

Kinderhook Series.—The oldest Mississippian deposit that is seen in the section along Mississippi River consists of black or dark-colored shale

[1] The name Valmeyer is proposed by J. M. Weller and A. H. Sutton to include beds from the base of the Osage group to the top of the Ste. Genevieve limestone and strata of equivalent age.

that rests unconformably on Devonian or older Paleozoic rocks. This deposit (termed Sweetland Creek in Iowa and Illinois, and Grassy Creek in northeastern Missouri) is about 100 feet in maximum thickness, and it is fairly widespread as shown by well borings and outcrops. Locally, especially to the south, it thins and disappears. The black shale is fairly uniform in character and evenly bedded. It carries a scanty fauna of marine or perhaps brackish-water fishes, thin phosphatic-shelled brachiopods, and a few other organisms.

Southeastern Iowa and northeastern Missouri contain excellent exposures of the beds which next overlie the basal Mississippian shale. These beds consist, in ascending order, of a limestone (Louisiana), a

Fig. 147.—Salem ("Indiana") limestone in a quarry near Bloomington, Ind. The limestone is sawed in large blocks, the vertical face shown in the photograph being due to sawing. Note the large "suture joint" or stylolite. (*Carey Croneis, University of Chicago.*)

calcareous sandy shale and fine sandstone (Hannibal), and an upper limestone (Chouteau). These formations vary a good deal in thickness in different exposures, their average total being a little over 100 feet. They appear to be rather local deposits on the northeast side of the Ozark Uplift. The limestones are mostly very fine-grained and somewhat thinly bedded, contrasting markedly with the limestones of the next overlying group. Fossils are very abundant in some beds. All of these Early Mississippian formations are classed together under the term Kinderhook series.

Valmeyer Series.—We come now to the most prominent and in some respects the most interesting Mississippian formations of the type section, which are grouped under the term Valmeyer series. This name is derived from southern Illinois, where the rocks of this series are well exposed. The Valmeyer beds in the Mississippi Valley region consist almost exclusively of limestone, and they attain a maximum thickness of more than 1,000 feet. High bluffs along the Mississippi, Missouri, and many tributary streams where these rocks occur contain splendid exposures.

The lower Valmeyer beds (Osage group) consist mostly of coarse-grained, crystalline, and thick-bedded limestone. Many layers are almost entirely composed of the remains of crinoids, which accordingly must have covered the shallow sea floor in extraordinary numbers. Whitish or bluish chert is common. It occurs in thin bands or lenses or in large rounded masses 2 or 3 feet wide and 1 to 2 feet thick. Some of this chert is very fossiliferous, indicating that the silica has replaced parts of the original limestone, enclosing and preserving the contained fossils. This is the more interesting since in many cases the limestone around the chert has been so recrystallized that a majority of the original fossils have been obliterated. Another feature that is very common and well shown is a peculiarly ragged suture-like joint (*stylolite*) subparallel to the bedding. Limestones of different color and texture may lie on opposite sides of a stylolite, interpenetrating one another as much as 12 inches in some cases. There is commonly a thin film of clay along the joint. The stylolites are apparently due to removal of parts of the limestone beds by differential solution and compaction of the remaining beds under pressure of the overlying strata.

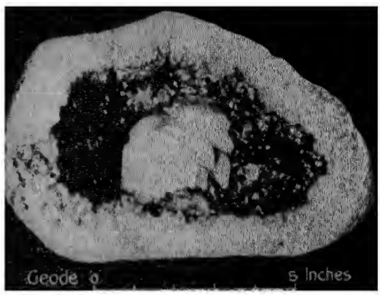


FIG. 148.—A geode broken in half to show the hollow interior, from the Warsaw formation, near Warsaw, Ill. (*Illinois Geol. Survey.*)

The basal part of the Valmeyer series consists of yellowish impure magnesian limestone, or of partly reddish limestone and calcareous shale beds (Fern Glen), that rest disconformably on the underlying Kinderhook or older rocks but grade upward without break into the overlying beds. The average thickness of these beds is about 40 feet. The next part (Burlington) averages a little over 100 feet in thickness and includes the most thick-bedded, light-colored crinoidal limestone of the Osage group. Some of the beds are very pure, consisting of more than 99 per cent calcium carbonate. The third formation (Keokuk), about 70 feet thick along the Mississippi River in southeastern Iowa, is more thinly bedded and bluish in color and many of the fossils differ from those of the underlying beds. The succeeding limestone and associated very fossiliferous calcareous shale (Warsaw) lie conformably on the Keokuk beds and the fauna is closely similar in many features to that of the subjacent rocks. The maximum thickness of Warsaw strata, in southern Illinois, is about 250 feet. A characteristic feature of this formation in many places is the common occurrence of geodes. These are hard concretionary masses of irregularly spherical form, mostly several inches in diameter. The

interior of the concretion is hollow or filled to varying extent with mineral deposits of different sorts that often show beautiful crystals.

The upper Valmeyer formations (Meramec group) are best exposed in the vicinity of St. Louis. The lithologic and paleontologic characters of these beds are broadly distinguished from those of the underlying strata. Apparently conformable upon the Warsaw formation, but not everywhere clearly differentiated, are thick beds of fragmental or granular, partly oolitic limestone (Salem) that contains large numbers of small brachiopods and other fossils. This formation, which is named from a locality in Indiana, occurs in western Illinois and extends as far north as southern Iowa. Its maximum thickness, observed in southeastern Missouri, is 160 feet. The next higher formation is a blue-gray, very fine-grained, dense, thick-bedded limestone (St. Louis), which is much less fossiliferous in most places than some of the associated formations. The thickness of this limestone near St. Louis is about 300 feet. At the top of the Middle Mississippian series is a prominent light-colored, commonly oolitic limestone (Ste. Genevieve) that is best developed in southeastern Missouri, southern Illinois, and western Kentucky. Locally, there is a disconformity at the base of this limestone, but elsewhere the boundary at the base is arbitrary. Some beds are hardly distinguishable in lithologic character from the typical St. Louis limestone. Sandstone occurs in a part of the formation in southern Illinois. The maximum thickness of the Ste. Genevieve beds is about 320 feet (western Kentucky).

Chester Series.—The Upper Mississippian rocks are classed together under the name Chester series. The type section of these beds, which is located in southern Illinois, shows a total thickness of about 1,200 feet. The strata consist of interbedded limestone, shale, and sandstone, all of variable lithologic character. There are very many changes in the nature of the rocks vertically, but each of the dozen or more formations that have been differentiated are fairly persistent horizontally. A distinct, widespread disconformity separates the Chester rocks from underlying Middle Mississippian formations. In southern Illinois the basal Chester consists of sandstone or of sandy shale and limestone that in places contain pebbles derived from the older rocks. Locally, the bottommost Chester beds are found resting on various parts of the Ste. Genevieve limestone or on the St. Louis limestone. These pre-Chester formations were subjected to gentle folding and erosion before the beginning of Upper Mississippian sedimentation in this region. Elsewhere, the break between Valmeyer and Chester deposits is strongly defined. The entire upper half of the Middle Mississippian strata is absent on the southwest flank of the Ozarks, and Chester deposits occur directly on beds as old as the Burlington. There is a widespread hiatus at the base of Chester formations in the Appalachian region also, the

next underlying strata ranging in age from St. Louis (or possibly Ste. Genevieve) to very early Valmeyer.

The limestones of Chester age in the southern Illinois and western Kentucky region are mostly thin-bedded, fine- to medium-grained rocks, ranging in color from light-gray to almost black. Oolite is prominent in places. Some beds are very cherty. Shale occurs between most of the thin limestone beds and is associated with some of the sandstones. Most of the shale is calcareous and light-colored, some is carbonaceous and nearly black, and a few beds are strongly ferruginous and red-colored. The sandstones are in part thinly bedded, ripple-marked somewhat shaly formations, and in part they are massive and irregularly cross-bedded. Almost all of the sandstones are fine-grained and yellowish brown in color. A few thin beds of coal occur. Fossils are extraordinarily abundant in some of the shale and limestone beds. The Chester fauna is readily distinguished from that of the preceding Mississippian formations.

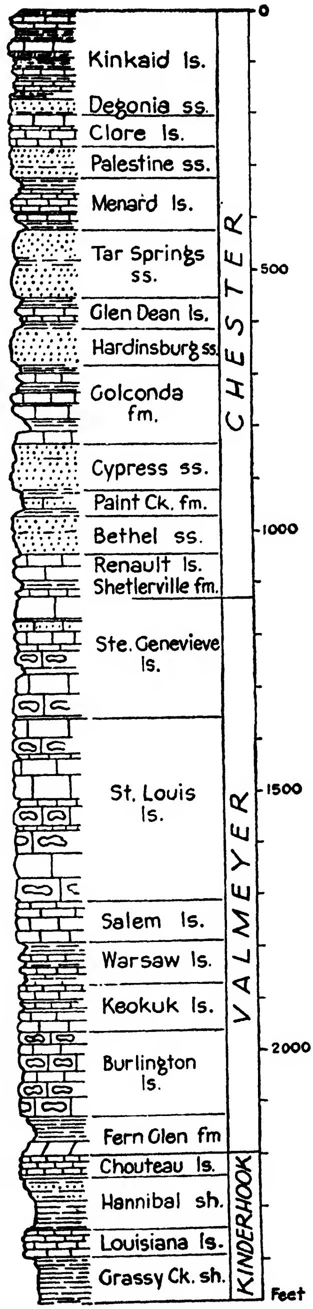


Fig. 149.—Generalized section of Mississippian rocks in the type region.

An interesting feature of the Chester series in the Mississippi Valley area is the occurrence of a fairly regular succession of alternating sandy and calcareous formations. A sandstone formation that rests disconformably on the next older beds is followed conformably by a formation consisting of limestone interbedded with shale. Above the limestone is a disconformity and another pair of sandstone and limestone formations. The disconformities evidently denote temporary retreats of the sea from the region under consideration. The sandstones comprise the initial, mainly terrigenous sediments of the readvancing seas, and the conformably overlying limestones and shales are deposits made in the clear shallow waters of the stages of maximum inundation. At least eight such cycles of advance and retreat of the Chester sea are recorded in the south-

ern Illinois and Kentucky region. The causes of this remarkable rhythmic oscillation of the sea level are obscure, but we shall observe that much the same sort of rhythm characterizes a great deal of the sedimentation of Pennsylvanian time.

The Lower Ohio Valley Regio..

Extensive outcrops of Mississippian rocks that appear in Indiana, western and south central Kentucky, Tennessee, and northwestern Alabama may be considered together.

The *Lower Mississippian* series is represented by black shale (Chattanooga) which is less than 50 feet in average thickness but is present throughout all of this region. Black shale (New Albany), partly Upper Devonian and partly Lower Mississippian, is 400 to 500 feet thick in southern Indiana and western Kentucky. A thin limestone of late Kinderhook age occurs locally in Indiana. It is interesting chiefly because it contains cephalopods that are seemingly identical with index fossils of the Early Lower Carboniferous of Belgium.

The *Middle Mississippian* beds of the lower Ohio Valley region are partly similar and partly very unlike corresponding strata of the type section. The Indiana-Kentucky area contains shale with thin limestone and sandstone beds, 500 to 800 feet thick, in the lower part, and limestones, 300 to 400 feet thick, in the upper part. The Salem limestone of south central Indiana is quarried on a huge scale for building stone. The Tennessee-Alabama area contains about 300 to 400 feet of Middle Mississippian limestones, representing all of the formations (except Upper Burlington) in the type region. The lower beds are exceedingly cherty.

The *Upper Mississippian* beds are similar in character and continuous with the Chester formations of southern Illinois. Limestone belonging in the lower part of the series is especially prominent in west central Kentucky, where there are thousands of caves and sink holes formed by the solvent action of ground water on the Chester and Valmeyer limestones. Mammoth Cave is the best known of the larger caverns.

The Appalachian Region

The Mississippian system is represented by outcrops in the western part of the Appalachian Mountains belt extending from Pennsylvania to Alabama. The rocks are folded and in places broken by large thrust faults, the outcrops occurring in elongate bands that are bordered on one side by Devonian rocks and on the other by Pennsylvanian formations. The Appalachian Plateau region, in which the strata are subhorizontal, is underlaid by Mississippian rocks, and the outcrops along the western margin of the plateau in Ohio and eastern Kentucky are included in describing this region,

The outstanding feature of the Mississippian formations in the Appalachian district is the great preponderance of shale and sandstone over limestone. Also, much of the shale and sandstone is of nonmarine origin. The total thickness of these rocks in parts of the Appalachian region is more than 5,000 feet. This is considerably greater than the thickness of the system in the lower Ohio or Mississippi River sections.

Lower Mississippian deposits consisting of black shale are widespread in Ohio, eastern Kentucky, and the southern Appalachians. There is

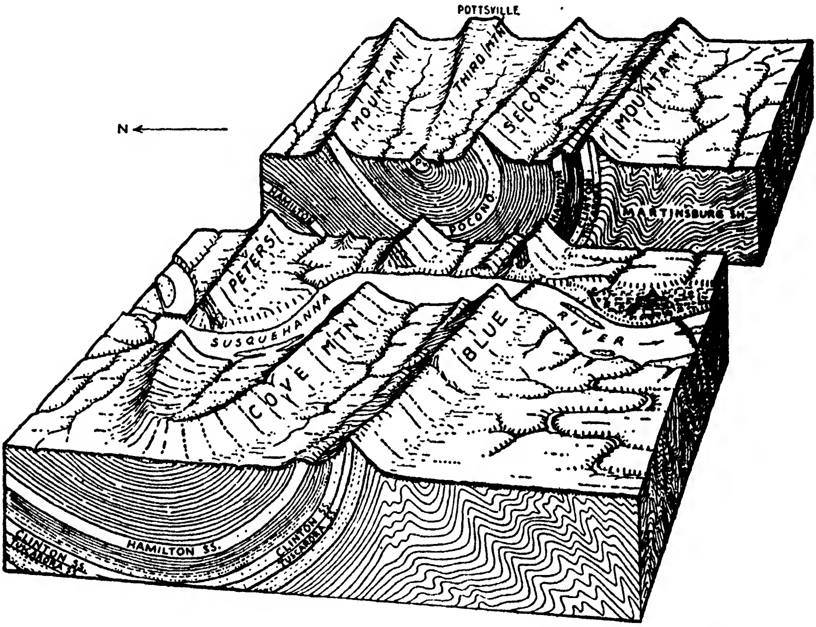


FIG. 150.—Diagram showing structure and topographic expression of Mississippian and associated formations in southeastern Pennsylvania near Harrisburg. The Mississippian rocks include the resistant Pocono sandstone which makes Peters, Cove, and Second Mountains, and the overlying soft shale (Mauch Chunk) which makes valleys. (*D. W. Johnson, Columbia University Press.*)

also a thin but extensive sandstone (Berea) which in the east forms the basal part of the prominent Pocono sandstone. The thickness of Lower Mississippian beds reaches a maximum of about 300 feet.

Rocks of *Medial Mississippian* age consist almost entirely of sandstone and shale (Pocono) which toward the east increase in thickness, in predominance of sand, and in coarseness. The sandstone attains a maximum thickness of about 2,000 feet. It is resistant to erosion and therefore makes prominent mountain ridges. In Ohio, the equivalents of the Pocono consist largely of shale (Cuyahoga) and overlying sandstone and shale (Logan) with a total maximum thickness of about 900 feet. These beds are all of very early Valmeyer age, the later Medial Mississippian being absent (unless the thin Maxville limestone of this region,

possibly of Ste. Genevieve age, belongs here). Southwestern Virginia and eastern Tennessee contain both early and late Medial Mississippian rocks, the latter including some red shale with salt and gypsum deposits (possibly of Warsaw age) overlaid by Meramec limestone.

The *Upper Mississippian* of the Appalachian region commonly begins with limestone (Greenbrier) of early Chester age that rests unconformably on lower Middle Mississippian. This limestone, interbedded with shale, has a maximum thickness in southern West Virginia where it is about 1,500 feet and represents a considerable part of Chester time. Northeastward, the limestone becomes very thin and disappears in Pennsylvania. The overlying strata consist of red shale alternating with thin red sandstone beds (Mauch Chunk), the thickness ranging from a very few feet in the west to about 3,000 feet in eastern Pennsylvania and 3,450 feet in southern West Virginia. Physical characters, such as color, irregularity of beds, abundant cross-bedding, distribution of thickness and coarseness, presence of mud cracks, rain prints, and organic evidence, such as the poorly preserved remains of land plants, tracks of land animals, and absence of marine fossils, indicate that these Late Mississippian deposits are of continental origin. They probably represent sedimentation by streams that flowed westward from Appalachia, building a low-gradient piedmont fan. The conditions are thus comparable to those of Late Devonian time in this region, except that the average texture of the land deposits of Mississippian age is much finer. The Mauch Chunk beds are soft and easily eroded, forming valleys.

The Michigan Basin

The Mississippian area of Michigan is fairly large, but because of a thick covering of glacial drift the rock strata are not well exposed. The total thickness of the system in this region is 2,000 feet or less, all of which belongs to the Lower and Middle Mississippian. The succession and general character of the beds are most similar to those of the Ohio section, shale and sandstone strongly predominating. The upper part of the Middle Mississippian contains about 200 feet of beds in which anhydrite, gypsum, dolomite, and salt are prominent. This gives evidence of evaporation of a part of the Mississippian sea, and it appears to correspond in age to the salt- and gypsum-bearing beds of southwestern Virginia.

The Mid-Continent Region

Southwestern Missouri, southeastern Kansas, northern and central Arkansas, northeastern and southern Oklahoma, and central and western Texas contain outcrops of Mississippian formations. In addition, many thousands of deep wells have penetrated the Mississippian in the Mid-Continent oil fields, so that the distribution and general character of the system beneath the surface are known over a large territory.

Lower Mississippian beds are widespread, being represented mainly by black shale (Chattanooga) that is exposed on the flanks of the Ozark Uplift and recognized in wells throughout much of Kansas and Oklahoma. The unconformity at the base of the Mississippian in this region is strikingly shown by the observation that in different places the black shale

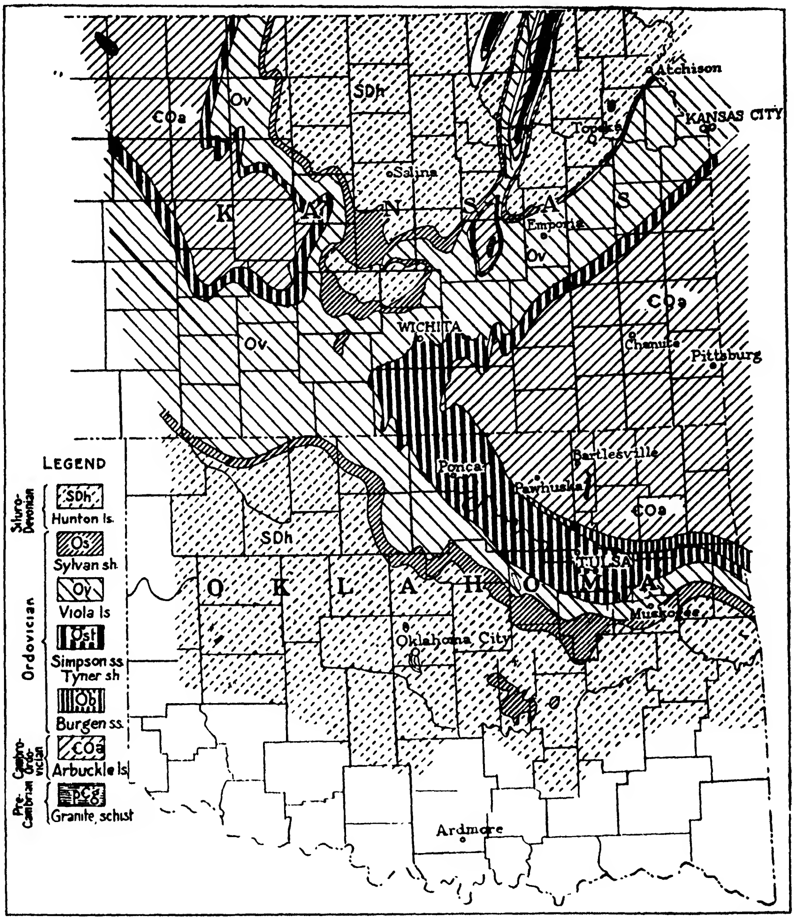


FIG. 151.—Map of Kansas and Oklahoma showing distribution of formations beneath the Mississippian rocks.

The map shows the outcrop areas that would appear if the Mississippian and overlying rocks were removed. (*After H. W. McClellan.*)

rests on the eroded surface of all older Paleozoic formations down to the Cambrian, and locally it lies on pre-Cambrian. By means of information from wells it is possible to mark out the area of contact of each pre-Mississippian formation with the basal Mississippian black shale; and this, obviously, shows what would be the outcrop of each pre-Mississippian formation if all of the Mississippian and younger rocks were removed. A map showing the distribution of outcrops in a region at some given

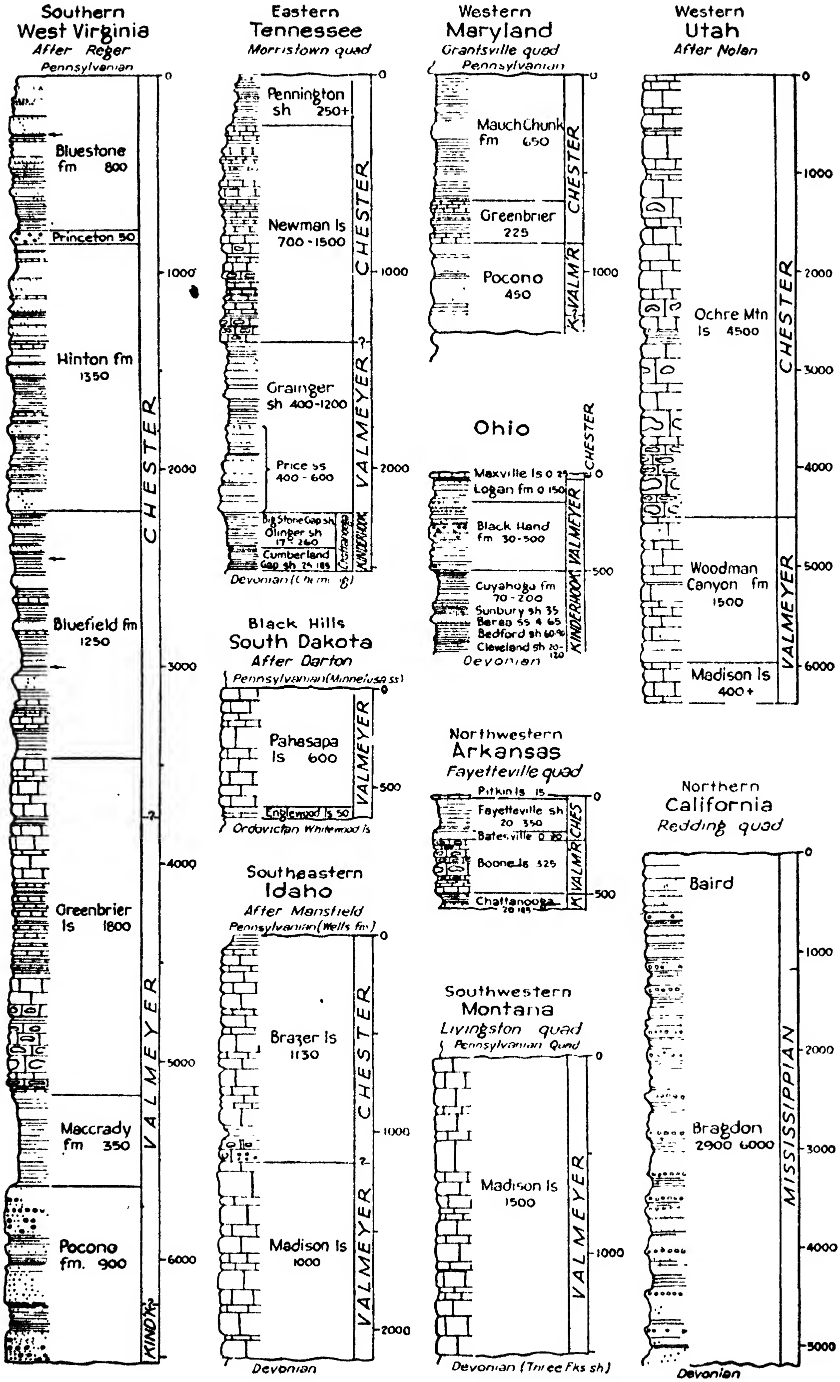


FIG. 152.—Sections of the Mississippian system in selected areas.

time in the geologic past may be termed a paleogeologic map, for it represents areal geology at an ancient time. This kind of map of the Mid-Continent region representing outcrops of formations at the beginning of Mississippian time (Fig. 151) has much economic value, for some of the pre-Mississippian formations are commonly found to be important containers of oil while others are not, and the map shows where the oil-bearing formations are present. The map also affords information (if the thickness of the formations is known) as to the depth of oil-bearing strata at a given place beneath the base of the Mississippian rocks.

The Ouachita and Arbuckle Mountains areas in southern Oklahoma and Arkansas contain Lower Mississippian beds consisting largely or wholly of chert, and in the Arbuckle Mountains there is an upper Kinderhook limestone that ranges to 200 feet in thickness.

Middle Mississippian formations appear to be confined to the northern part of the Mid-Continent region, except for thin deposits on the flank of the Llano Uplift in central Texas. The beds consist of massive, medium- to coarse-grained, crystalline limestone that commonly contains a very large amount of chert. Much of southwestern Missouri and neighboring territory in other states is mantled by nodules and angular fragments of Mississippian chert that have been left as a residue by weathering of the limestone. The age of the limestone ranges from Fern Glen to Warsaw. Strata of later Valmeyer age also were deposited in this region but they were almost entirely removed by erosion before Chester time. Early Mississippian limestones underlie most of Kansas and northern Oklahoma, where they are commonly designated as the "Mississippi lime."

The *Upper Mississippian* is represented in northern and central Arkansas, southern Oklahoma, and Texas. The beds on the south flank of the Ozarks in northern Arkansas consist of thick marine black-shale deposits and some sandstone and limestone. There are beds (Caney) of corresponding age and character adjacent to the Arbuckle Mountains. These formations rest unconformably on Middle or Lower Mississippian rocks. Deep drilling has recently shown the existence of 800 feet or more of Chester sediments in northwestern Oklahoma. The Ouachita Mountains contain a great thickness (to 6,000 feet) of mostly unfossiliferous dark shale beds alternating with fine-grained greenish sandstones, and these are followed by massive sandstones with a reported thickness up to 6,600 feet. Scanty land-plant remains indicate that the lower of these formations is probably Upper Mississippian, and the thick sandstone may belong here also, but this is not yet established definitely.

Western North America

Limestone deposits of Mississippian age are distributed over very large areas in the western United States and Canada. The most wide-

spread and prominent portion of the deposits is that called Madison limestone, a very massive, fairly uniform light-gray rock that commonly forms sheer cliffs. Its average thickness is about 300 feet, but in northwestern Wyoming it is 1,600 feet thick. The summit portions of the Bearpaw Mountains and other mountain uplifts in Montana are made by the Madison limestone. The most striking cliff maker in the Grand Canyon region is also this limestone, which, however, is designated here by the name Redwall. The fossils occur rather sparingly in most places but they show that the Madison is of lower Osage age, that is, Fern Glen to Keokuk, inclusive. The upper Middle Mississippian appears to be lacking in the western region, unless certain limestone beds of Montana

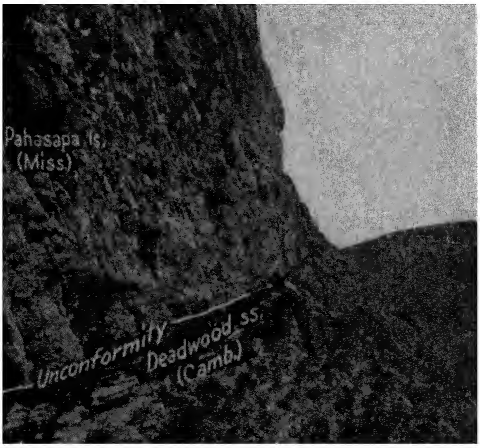


FIG. 153.—Mississippian limestone resting disconformably on Cambrian sandstone, near Nowood, Wyo. (*N. H. Darton, U. S. Geol. Survey.*)

are of St. Louis age. Upper Mississippian or Chester limestone beds are found in Nevada, Utah, Wyoming, Idaho, and California.

Maritime Provinces of Canada

Mississippian deposits of continental origin are found in Nova Scotia, New Brunswick, and eastern Quebec. They consist of coarse conglomerate, sandstone, and siliceous shale (Horton and Albert beds) which have a total reported thickness up to 3,400 feet. Locally these beds rest on steeply upturned, erosion-truncated Devonian and Silurian strata, and in the conglomerates there are pebbles of fossil-bearing older Paleozoic limestones. Some of the Mississippian strata contain abundant remains of land plants, including numerous stumps and trunks of small trees standing erect in the position of growth; there are also remains of many fresh-water fishes.

The later part of Mississippian time is represented in the eastern Canadian region by conglomerates, sandstones, shales, thin dolomitic

limestones, and much gypsum (Windsor and Cheverie series). These rocks are largely marine and some of the beds contain numerous fossils. The faunas appear to be more related to those of Lower Carboniferous deposits in England than to other Mississippian faunas of North America. The thickness of these rocks, which occur in New Brunswick, Nova Scotia, and Newfoundland, is about 2,000 feet.

MISSISSIPPIAN FORMATIONS OF OTHER CONTINENTS

Europe.—Rocks of Mississippian age are widespread in Europe and in some parts of the continent they attain a thickness of more than 5,000 feet. The name Lower Carboniferous is commonly used but the formations included under this term in Europe are as clearly entitled to rank as an independent geologic system as the corresponding rocks in America. The so-called Lower and Upper Carboniferous are separated in practically all European localities by a well-defined disconformity or unconformity, and there are distinguishing paleontologic and lithologic characters like those that separate Mississippian and Pennsylvanian deposits in the United States. The Lower Carboniferous rocks were strongly folded and beveled by erosion in several parts of western Europe before deposition of Upper Carboniferous beds.

The Lower Carboniferous in most of western Europe consists of massive limestone containing many marine fossils. This has been called the Mountain limestone in Great Britain, but it is more commonly known at present as the Carboniferous limestone (Kohlenkalk). Chert is abundant in some beds. The total thickness of the limestone, including associated minor shaly and sandy beds, is about 3,000 feet in Ireland, and, including a larger proportion of shale, sand, and some coal beds, the thickness exceeds 7,500 feet in north central England.

Part of southern England and much of continental Europe east of the Rhine contain a different type of Lower Carboniferous deposits consisting of dark shale, sandstone, and some conglomerate, but almost no limestone. These deposits, which are called Culm beds, are equivalent in age to the thick marine limestones. They contain a distinctive grouping of molluscan fossils among which are cephalopods, and therefore the beds are marine or at least brackish-water in origin. There are also some layers that contain land plants, and lateral gradation into continental deposits containing coal beds is observed. The sandy and shaly, in part coal-bearing, portion of the Lower Carboniferous deposits in Europe is similar in many ways to the Mississippian deposits of the Appalachian region in North America which also grade westward into thick limestones. Workable coal beds of considerable economic importance occur in the Lower Carboniferous of southern Russia (Donetz Basin) where the thickness of the system is reported to reach the very large total of 22,000 feet.

Other Continents.—Asia contains widespread Lower Carboniferous marine beds, the most important areas being found in Asia Minor, Persia, southwestern Siberia, and China. Marine and nonmarine deposits of Mississippian age occur also in Australia, northern and southern Africa, and in South America (mainly Argentina, Chile, Bolivia, and Brazil).

PHYSICAL HISTORY OF MISSISSIPPIAN TIME

The main features of Mississippian history, as regards North America in particular, may now be set down in chronologic sequence, statement of the changing conditions in different regions being based on observation and interpretation of the Mississippian formations that have been described.

Early Mississippian Epoch.—At the beginning of Mississippian time the Appalachian borderland appears to have been still moderately elevated, for large quantities of sand, silt, clay, and some gravel are found in the Lower and Middle Mississippian rocks of the Appalachian geosyncline. These land-derived sediments were spread westward into the Ohio Valley but were not carried far beyond the Cincinnati Upwarp. The northern, central, and western parts of the continent were evidently very low land at the beginning of the Mississippian period. Much of this territory had been submerged in Late Devonian time, indicating general lowness then; but there is a hiatus between the latest Devonian and earliest Mississippian, showing that there was some emergence. The Early Mississippian deposits of the interior are neither very thick nor preponderantly sandy, and thus they denote an absence of extensive erosion of land areas.

Except a thin and rather local veneer of sand, the initial Mississippian deposit in most of the central part of the continent is black shale. In the Ohio Valley region this black shale marks a continuation or resumption of conditions that had prevailed in the Late Devonian, but over a large area west of the Mississippi and apparently also in the Tennessee-Alabama region the shale was spread over country that had been land during Late Devonian time. The conditions of sedimentation represented by the black shale are not clearly understood, but it is certain that the shale was deposited in a shallow continental sea. That the sea was not exactly of the normal type is shown by the very restricted assemblage of fossils which include certain invertebrates of marine derivation that were probably adapted to brackish-water conditions, an abundance of land-plant spores, and not uncommon pieces of wood. The spores could readily have been transported by wind, and the wood could have been floated to the sea area by streams. Perhaps the blackness of the shale is largely due to occurrence of black humus-rich soils on land adjacent to this sea, the material of the soils being the chief source of the shale sediments; such black soils are common today in some regions, as especially in parts of Russia. Whatever may have been the conditions of origin, the making of black shale deposits is one of the important features of Early Mississippian time.

The occurrence in the upper part of the Lower Mississippian series of local limestone and shale formations and some sandy beds containing abundant marine fossils of normal aspect shows a change in conditions following deposition of the black shale. Absence of these later formations in many places implies emergence during this part of Kinderhook time. Apparently the late Kinderhook sea did not extend far east of the Mississippi but it submerged a large area in the west that had previously been land. Strongly marked local variations in the character and thickness of the Early Mississippian formations on the flanks of the Ozark Uplift

suggest that the sea surrounded but did not cover the central part of the uplift, which accordingly would make a fairly large island. Some of the Kinderhook sediments were certainly derived from the Ozark area, and slight differences in faunas on opposite sides of the uplift may represent differences in environment that were due mainly to existence of the large island.

Medial Mississippian Epoch.—The chief feature of Medial Mississippian time is a great expansion of the sea in the interior and western portions of North America, and the accumulation in the clear waters of this sea of thick beds of limestone, some of which abound in well-preserved fossils. The fact that the basal subdivision (Fern Glen) of the

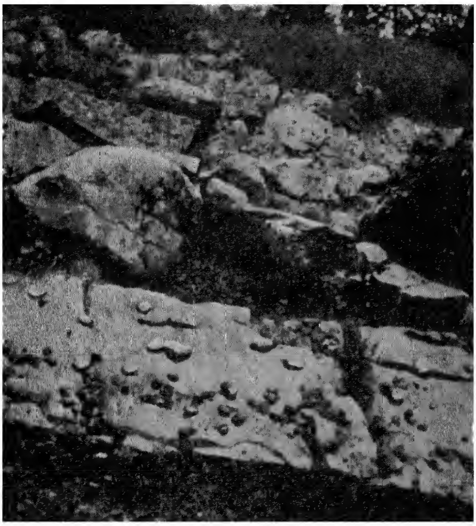


FIG. 154.—Cherty St. Louis limestone, Tazewell County, southwestern Virginia. (*Charles Butts, U. S. Geol. Survey.*)

Middle Mississippian series is about as widespread as any of the higher ones furnishes evidence that the marine transgression at the beginning of this epoch was relatively rapid, and, although there were some fluctuations of sea areas during the epoch, the conditions were fairly uniform for the long time represented in the making of the limestone deposits. The region of submergence, as shown by the distribution of Middle Mississippian marine formations, includes most of the Mississippi Valley, the lower Ohio and southern Appalachian areas, and the very extensive western region that includes the Rocky Mountains, Great Basin and southwestern states, and also much of western Canada.

Although Mississippian rocks are now absent from all of the central part of the Ozark Highlands, the occurrence of residual Middle Mississippian fossil-bearing cherts in this region affords evidence that the lime-

stones in which the cherts were originally formed extended entirely across the Ozark area. The former Ozark island was submerged. Supporting testimony is found in the extremely small amount of silt or clay in most of the limestones of Medial Mississippian age that are now exposed on the flanks of the uplift; also, there is general uniformity in the character of the fauna of each limestone formation on different sides of the Ozarks, which suggests that there were freedom of migration and similarity of environment on the shallow sea bottom throughout this region.

It is noteworthy that the youngest residual fossil-bearing cherts of the central Ozarks are of Warsaw age, which may signify that the later Valmeyer seas did not submerge all of the Ozark Uplift. Coincidently, there is a change in certain constituents of the Middle Mississippian limestones, for study of insoluble residues (made by dissolving rock samples in acid) shows an absence of quartzose and heavy-mineral sand grains in the Warsaw and older Valmeyer limestones but the appearance of these grains commonly in the St. Louis and Ste. Genevieve beds.

Examination of the Middle Mississippian limestones along the Mississippi River calls attention to the greater thickness of the formations and lesser prominence of lines of separation between successive formations in the south than in the north. The deposits in the north are much thinner and there are erosional breaks between many of the formations, or even within certain formations. This shows that the sea was practically continuously present in the southern territory, that is, south of St. Louis, but it was alternately present and absent in the north, as in Iowa. These conditions mark oscillations of the sea margin toward the land which in this area lay north of Iowa.

The Appalachian region and Michigan contain evidence of sandy and muddy sea-bottom conditions during Medial Mississippian time, and also of extensive flood-plain or alluvial fan deposition by streams that flowed westward from Appalachia. Both in the south central Appalachians and in Michigan there are red beds, salt, and gypsum beds which give proof of the drying of saline basins.

Late Mississippian Epoch.—The distribution of marine Chester formations shows that there were important geographic changes in the latter part of Mississippian time. The sea that had occupied the south central part of the Mississippi Valley fairly continuously during earlier epochs spread far to the east, reaching Pennsylvania and Virginia; to the northwest it extended over much of the Cordilleran region, and to the southwest across Oklahoma and western Texas. The fact that the Late Mississippian deposits rest disconformably on older rocks in most of these regions affords record of at least temporarily emergent conditions preceding the advance of the Chester sea. The total area submerged during some portion of the Late Mississippian epoch is somewhat less than that of the preceding epoch, but in parts of the Appalachian region the only limestone, if not the only marine deposit, of the Mississippian system belongs to the lower Chester series. It is certainly true that the

present known distribution of Late Mississippian formations is less than the actual original distribution, for erosion in the closing part of Mississippian time or early part of Pennsylvanian time removed most or all of the Chester beds in some places where there is evidence that they were once existent; also, erosion in other parts of post-Mississippian time has reduced the area of Chester deposits. At any rate, the considerable spread of the early Chester sea is one of the chief features in the history of this epoch.

The region extending from southern Illinois to southwestern Virginia, including parts of Kentucky, Tennessee, Alabama, and West Virginia, was the site of thick limestone deposition. Much of this limestone is oolitic, and the total thickness of Chester limestones is locally at least 1,000 feet. A peculiarity of the Late Mississippian deposits in much of this region is the alternation of sandstone and limestone formations which has been noted previously, and this appears to mean that the sea advanced and retreated considerable distances several times during the epoch.

Continental sedimentation consisting of red shale and sandstone was extensive during Late Mississippian time in the Appalachian region. The deposits laid on land are contemporaneous with marine formations to the west, for they grade laterally into the marine beds or are interfingered with them. The very thick dark shale and sandstone (6,000 to possibly 12,600 feet) of Late Mississippian age in the Ouachita Mountains of Arkansas and Oklahoma are certainly water-laid, apparently marine, deposits, although remains of land plants occur in places. These sediments were carried northward from a large land mass to the southeast that is called Llanoria.

Close of the Period.—The erosional break that separates Mississippian from Pennsylvanian formations almost everywhere indicates clearly the very general elevation of North America and the withdrawal of continental seas at the close of Mississippian time. There was accordingly an interval of nondeposition of sediments in the areas exposed for observation, and in addition there was undoubtedly some erosion.

Well records in Kansas and Oklahoma show that contact between the Mississippian and Pennsylvanian strata is distinctly uneven in many places. There are ridges and hills of hard Mississippian limestone that rise 100 feet or more above the general base of the Pennsylvanian shale and sand, and there are valleys 75 feet or more in depth that were carved in the limestone and filled by Pennsylvanian sediments. Similar topographic irregularities with a relief of as much as 300 feet are observed at the Mississippian-Pennsylvanian contact in parts of Kentucky. Residual chert and other coarse detritus at the top of the Mississippian in the Mid-Continent region are important reservoirs of oil and gas. Faulting that involves the Mississippian formations but does not affect Pennsyl-

vanian beds is observed in southern Illinois and western Kentucky. There was thus a broad epeirogenic or warping movement of the earth crust toward the close of the Mississippian period that raised the continent, and locally there was faulting.

Folding and faulting of considerable magnitude affected the deposits of Mississippian age in western Europe, and this occurred before the time of deposition of Early Pennsylvanian rocks that rest unconformably on the disturbed and eroded Mississippian strata. Two main belts of mountain building are thus defined, one extending through southern Ireland to central Germany, and another trending eastward from southern France to Bohemia. Much igneous activity, including intrusions and extrusions, accompanied this deformation.

Evidence of mountain making in North America at or near the close of Mississippian time is observed in the Mid-Continent and Appalachian regions. Along the flanks and buried crest of the Wichita Mountain axis in southern Oklahoma and northern Texas, Early Pennsylvanian beds rest on steeply folded and faulted older Paleozoic rocks, probably including Mississippian. There is no evidence that the deformation of the pre-Pennsylvanian rocks occurred before the close of Mississippian time, but, as indicated in the next chapter, the disturbance may belong in the early part of Pennsylvanian time. Similarly, the buried Nemaha Mountains that extend from southeastern Nebraska to central Oklahoma were formed at the close of the Mississippian or early in the Pennsylvanian period. Pennsylvanian beds overlie tilted Mississippian rocks in New Brunswick.

Another sort of evidence bearing on the existence of mountainous elevations in parts of North America toward the end of Mississippian time is found in the very thick and in part very coarse sediments of Late Mississippian and Early Pennsylvanian age in the Ouachita and Appalachian Mountains. These sediments represent the products of erosion of mountainous highlands. The Ouachitas contain more than 20,000 feet of Late Mississippian and Early Pennsylvanian sandstone and shale. The Appalachians contain 10,000 feet or less of Early Pennsylvanian beds in which sandstone and conglomerate are very prominent, the latter having cobbles up to 6 inches in diameter. The name "Ouachita revolution," which has been applied to crustal deformation in North America near the close of Mississippian time, is rather misleading since there is little evidence of folding in the Ouachita Mountain area at this time; indeed, there is no evidence of a major disturbance of the Ouachita geosyncline until after Early Pennsylvanian (Atoka) time. The term *Culmide disturbance,* derived from Europe, is a preferable designation.

ECONOMIC PRODUCTS

The chief materials of economic importance obtained from Mississippian rocks are petroleum, natural gas, asphalt, coal, salt, gypsum, building stone, lime, cement, zinc, lead, and road material.

Oil and gas in fairly large quantities have been obtained from Mississippian sandstones and limestones in the Mid-Continent, Illinois-Indiana, and Appalachian fields. Rock asphalt is found in the Mississippian rocks of western Kentucky.

Coal occurs mainly in the Pocono beds of the Appalachian region, but the deposits are mostly too thin and impure to compete with the Pennsylvanian coals. A Mississippian coal bed, 10 to 14 feet thick, is mined in Virginia. Coal fields of much importance occur in southern Russia.

Salt is produced from Mississippian rocks in Michigan and Virginia, and gypsum is quarried also in the latter state.

The so-called "Bedford" or "Indiana" limestone of Medial Mississippian age furnishes more than one-half of the cut stone for building purposes used in the United

FIG. 155.—Air view of Picher, Okla., showing numerous "chat" piles consisting of waste rock (mostly chert) thrown out from lead and zinc mines in Mississippian limestone.

States. This stone comes from south central Indiana. Much limestone for buildings and monuments is quarried also in southwestern Missouri near Carthage. Because of its purity, some of the Mississippian limestones have been much used for manufacture of lime. There are also abundant supplies of good limestone and shale for use in making Portland cement. The Berea sandstone of Ohio has been used in making grindstones.

Zinc and lead ores are mined in large quantities near Joplin in southwestern Missouri, southeastern Kansas, and northeastern Oklahoma. The ores occur in Middle Mississippian limestone but were deposited there in post-Mississippian time. This is the chief zinc-producing area in the United States. Use for the great piles of chert that are thrown out from the mines has been found in crushing the chert and spreading the "chats" thus formed on roads.

SUMMARY

The Mississippian formations are equivalent to the Lower Carboniferous of European classification, but, because they are separated almost everywhere from the succeeding Pennsylvanian by a prominent uncon-

formity and because of general faunal and lithologic distinctions, the Mississippian rocks may be defined as constituting a geologic system.

The dominant type of rock in the Mississippian system of the Mississippi Valley and western North America is limestone, but in the Appalachian region the deposits consist chiefly of sandstone and shale which are partly marine but largely nonmarine. There are also thick shale and sandstone in the Ouachita Mountains of Arkansas and Oklahoma. The average thickness of Mississippian rocks in the Mississippi Valley is somewhat less than 2,000 feet, and in the lower Ohio Valley about 3,000 feet. In the Appalachian area they locally exceed 5,000 feet, and in the Ouachitas the total thickness is possibly over 12,000 feet.

Important outcrop areas of Mississippian formations occur along the Mississippi River between Iowa and the mouth of the Ohio, around the Ozark Highland, in the lower Ohio Valley, the Appalachian region, eastern Canada, Ouachita and Arbuckle Mountains, and in the western United States and Canada.

Three main divisions are recognized in the system: the Lower Mississippian or Kinderhook series, the Middle Mississippian or Valmeyer series, and the Upper Mississippian or Chester series.

The Lower Mississippian consists of widely distributed black shale in the lower part, overlaid locally by variable limestone, shale, and sandstone, some beds containing abundant fossils. The sea was much less extensive than later in the period.

An unconformity occurs in most places at the base of the Middle Mississippian series. The rocks consist almost wholly of limestone in the Mississippi River section and western half of the continent. Some of the formations contain an abundance of chert, and fossils are very numerous. Sandstone and shale belonging to the early part of this epoch occur in the Ohio Valley and Appalachian region.

The Upper Mississippian is separated from lower divisions by a widespread unconformity. In the Mississippi Valley region this series consists of alternating limestone and sandstone formations that indicate a rhythmic advance and retreat of the sea. The Appalachian region contains some limestone but the Upper Mississippian is composed mainly of continental red beds. Limestone belonging to this series occurs in the far west.

The close of Mississippian time is marked by mountain-making disturbances in western Europe (Culmide disturbance). There was a general elevation of North America which is recorded in the prominent unconformity between the Mississippian and Pennsylvanian deposits; and there were folding and faulting near the close of Mississippian time (or possibly in Early Pennsylvanian time) in the Mid-Continent. Thick, coarse land deposits of Late Mississippian and Early Pennsylvanian age in the Ouachita and Appalachian regions indicate the existence of mountainous elevations in Llanoria and Appalachia.

CHAPTER XVIII

FORMATIONS AND PHYSICAL HISTORY OF PENNSYLVANIAN TIME

The rock formations called Pennsylvanian are important because of their content of materials useful to man—coal, petroleum, natural gas, clay, and stone—and they are also interesting because of special features in their origin and geologic history. Workable coal beds in different parts of the world range in age from Devonian to Tertiary, but no other system approaches the Pennsylvanian in quantity of high-grade coal. Consequently, it is the leading source of the world's coal supply. The coal beds cover thousands of square miles and in some districts their aggregate thickness is several scores of feet. A large production of oil and gas is obtained from Pennsylvanian rocks, especially in the Mid-Continent region of the United States.

Some of the chief features in the historical geology of Pennsylvanian time in North America are (1) evidence of widespread erosion of the land before the beginning of Pennsylvanian sedimentation, (2) concentration of maximum thickness of deposits (to more than 25,000 feet) in geosynclinal areas, (3) dominance of continental and of coarser deposits in areas where the Pennsylvanian has maximum thickness, (4) very extensive coal formation, (5) repeated alternation of marine and nonmarine strata in the continental interior, and (6) mountain-building. Each of these features will be treated in some detail at an appropriate place in our study.

Definition and Stratigraphic Relations

The Pennsylvanian rocks are named from the state of Pennsylvania where there are extensive exposures and where the largest quantity of coal in the United States is mined. The coal-bearing strata in this region were among the first to receive attention in mapping and study, but for many years they were simply termed "Coal Measures" or Upper Carboniferous. The term Pennsylvanian is almost exclusively used in North America, but not in other continents. Most foreign and some American geologists employ the name Carboniferous for rocks of Mississippian and Pennsylvanian age. The United States Geological Survey includes Permian also as a division of the Carboniferous.

The Pennsylvanian formations rest unconformably on older strata in practically all observed exposures. In many places the upper surface of the older rocks is uneven, showing distinct hills and valleys that were formed by erosion before the Pennsylvanian sediments were deposited. Elsewhere the basal boundary of the Pennsylvanian is fairly even but the

fact that formations of different age, ranging from Late Mississippian to pre-Cambrian, occur next below the bottom of the Pennsylvanian shows the importance of the boundary. Land conditions accompanied by some erosion certainly preceded Pennsylvanian sedimentation almost everywhere. This widespread unconformity at the base of the Pennsylvanian, the extensive overlap of the younger on older formations, and a difference in structural attitude of these formations in many places, all serve to indicate that the Pennsylvanian represents a distinct chapter in earth history. It is therefore hardly fitting to regard the Pennsylvanian as a subordinate series in a geologic system, as is done by combining Pennsylvanian with Mississippian. Rather, the Pennsylvanian should be assigned the rank of a geologic system and the time represented by it should be termed a period.

The top of the Pennsylvanian is much harder to determine satsfactorily than the base, for in America the Permian follows the Pennsylvanian conformably, or with a break so slight that it is difficult to recognize. Accordingly, distinction is based on comparison of fossils with collections from type sections in Europe.

General Character and Thickness

The Pennsylvanian formations contain a larger proportion of nonmarine deposits and these are spread over a larger area than in any older Paleozoic system. In places, as along the Appalachian Mountains, continental sediments consisting of conglomerate, sandstone, shale, and coal far outweigh marine strata; in other places, as in Kansas and Nebraska, marine deposits consisting of limestone, shale, and sandstone are quantitatively more important than nonmarine. In general, the Pennsylvanian formations are characterized by alternating nonmarine and marine deposits which show that the sea repeatedly inundated and then uncovered large areas. The very numerous and extensive oscillations of land and sea are an outstanding character of the Pennsylvanian period in America and also of equivalent time in Europe.

Nonmarine Formations.—Nonmarine deposits of Pennsylvanian age include conglomerate, sandstone, shale, fresh-water limestone, and coal. The nonmarine origin of these rocks is indicated commonly by the presence of land-plant remains, by the absence of marine fossils, and in many cases by lithologic peculiarities, irregular stratification, and characters of thickness, form, geographic distribution, or relation to associated deposits. Traces of land animals are generally rare. It is difficult, or in some cases impossible, however, to distinguish nonmarine and marine rocks of certain sorts when fossil evidence is lacking.

Coarse conglomerates are found chiefly in the Appalachian region, and parts of southern Oklahoma, Texas, and Colorado. Fairly well-rounded pebbles an inch or two in diameter are common in some of the

formations, and in a few instances there are deposits formed largely of cobbles and boulders. Fine conglomerates that grade into sandstone are found also. The constituents of the conglomeratic rocks are mostly quartz, and this fact, together with the worn, rounded surface of the pebbles, indicates long transportation. Geographic distribution, lenticularity of some of the deposits, and relation to associated sedimentary strata indicate that the transporting agents were streams which must have had a fair velocity. In the vicinity of the limestone mountains of southern Oklahoma, there are coarse Pennsylvanian conglomerates composed chiefly of limestone pebbles and cobbles, which though carried only a few miles are fairly well rounded.

Sandstones of coarse, medium, and fine texture occur in the form of widespread layers and as lenses, the latter including masses of irregular shape and size that pinch out or grade laterally into shale. Very narrow and elongate sand lenses, called "shoestrings," are common in places. They are fillings of stream channels that were eroded at times of temporary exposure of the Pennsylvanian sediments.[1] Cross-bedding and

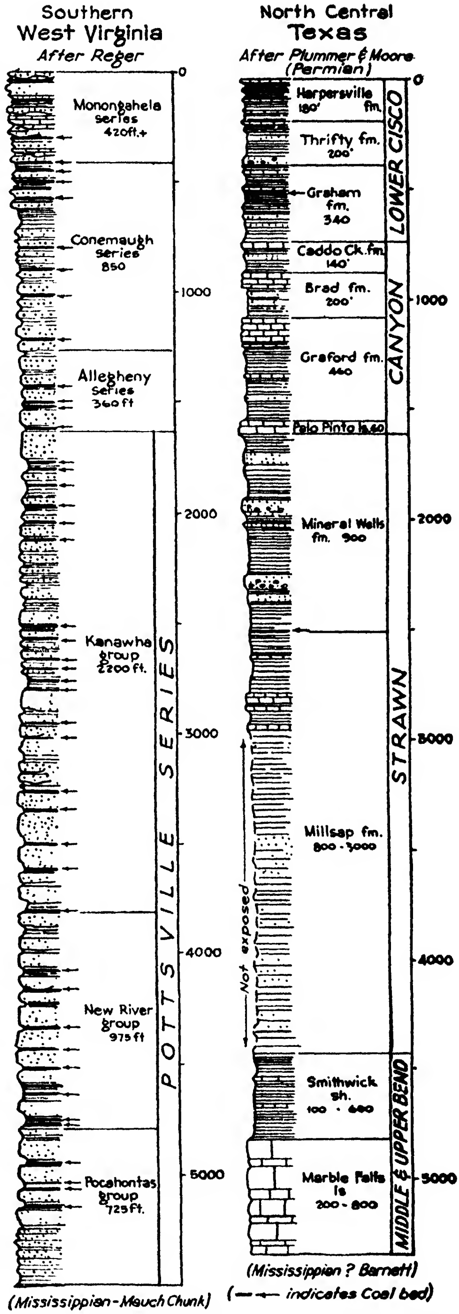


FIG. 156.—Sections of the Pennsylvanian system in West Virginia and Texas.

[1] It appears that some "shoestrings" are of marine origin, being formed as near-shore sand bars or barriers. These are distinguished by the convexity of their upper surface, whereas stream-channel fillings are marked by the convexity of the lower surface.

current ripples are characteristic of some beds, and in shaly rocks mud cracks may appear. The sandstone beds have a thickness of more than 100 feet in a few cases, though mostly they are much thinner. A yellowish-brown color prevails.

The shaly deposits of continental origin are variously colored—gray, bluish, brownish, and red all being common. Fine sandy or silty texture is prevalent and lamination is generally more poorly defined than in the marine shales. Carbonized fragments of land plants and in many cases also very beautifully preserved leaves and other parts of land vegetation are found in these shale beds.

Fresh-water limestones, distinguished by peculiarities of texture, absence of marine organisms, and occasional presence of fresh-water life, are found in parts of the Pennsylvanian deposits, especially in the Appalachian region.

The coal beds are an important part of the Pennsylvanian land deposits, consisting of the compacted and otherwise altered remains of land vegetation that grew in moist swampy areas. The conditions involved in the formation of the coal beds will be discussed in a later part of this chapter.

Marine Formations.—The marine Pennsylvanian deposits include several kinds of limestone, shale, sandstone, and a little conglomerate. The limestone beds are mostly light-colored, nonmagnesian, fine-grained, and fairly fossiliferous. Some beds are oolitic. Extreme abundance of the small spindle-shaped shells of the foraminifera called fusulinids gives a distinctive appearance to the beds containing them.

The marine shale deposits show about as wide color variation as the nonmarine beds, from which they are distinguished by presence of marine fossils and more uniform, well-defined lamination. Similarly, there are some evenly stratified marine fossil-bearing sandstones.

Lateral Persistence of Beds.—Many of the limestone, shale, and coal beds may be traced for as much as 500 miles along the outcrop with almost no change, and this applies to some of the very thin as well as the thicker beds. For example, in the Mid-Continent region, certain beds of limestone 6 inches to 2 feet thick are known to be continuous from Iowa to northern Oklahoma, and the beds show practically the same characters throughout this distance. The Pittsburgh coal of western Pennsylvania and adjacent states is known to extend throughout an area of more than 6,000 square miles, and some of the coal beds of the Illinois-Indiana basin are now recognized as continuous over an area of approximately 50,000 square miles. In a number of cases, coal beds 1 to 4 inches thick have been traced 200 to 300 miles. A microfossil zone ¼ inch thick has been identified in Kansas and Nebraska outcrops 100 miles apart. These observations point to very great uniformity in the conditions of sedimentation along the strike of these beds.

Alternation of Marine and Nonmarine Beds.—An especially interesting character of the Pennsylvanian deposits in much of North America is the repeated alternation of marine and nonmarine deposits. For example, in about 2,500 feet of Pennsylvanian strata in Kansas and Missouri there are not less than 50 changes from marine to nonmarine sediments or *vice versa.* Since these alternating marine and nonmarine strata are traceable for hundreds of miles along the outcrop and beneath the surface by means of well records, the advances and retreats of the sea are not mere local oscillations. The same sort of alternation is observed in Illinois and in part of the Pennsylvanian as far eastward as Pennsylvania.

Sedimentation Cycles.—The very numerous changes in the character of the Pennsylvanian beds in vertical sequence contrast strongly with their lateral uniformity and indicate very frequent changes in the nature of the physical conditions governing sedimentation. Nonmarine shale, commonly sandy, in places containing sandstone beds and at certain horizons coal beds, is overlaid by marine limestone and shale. The latter, in a number of cases, shows a definite sequence of several different types of limestone separated by thin shale beds, each with distinctive lithologic characters. The significance of these sequences that are repeated several times with surprising fidelity is not known, but the evidence clearly points to a cyclic rhythm of sedimentation.

A similar repetition of a certain definite sequence of beds is also a distinguishing feature of the eastern Pennsylvanian deposits (J. M. Weller). Beginning with sandstone, which commonly rests disconformably on the beds beneath, the sequence includes sandy or micaceous shale, underclay, coal, marine shale, and limestone. The beds from the sandstone to the coal, inclusive, are nonmarine and those above the coal are marine. Nonmarine sandstone above the marine rocks begins a new cycle, which includes coal and marine rocks, and so on many times.

Depth of the Pennsylvanian Seas.—Physical characters and the nature of the fossils contained in marine formations of the continents furnish basis for the conclusion that the depth of most parts of ancient epicontinental seas was less than 600 feet. Because of the repeated alternation of sea and land conditions that is evidenced in so much of the Pennsylvanian deposits, it is especially desirable to ask (1) whether the depth of the Pennsylvanian seas, on the average, was of the order of 500 or 600 feet and, accordingly, whether there were repeated up and down movements of the earth's crust of approximately this amount, or, on the other hand, (2) whether the depth of the seas was very small and the amount of crustal movements correspondingly slight. In the latter but not the former case, it is possible that movement of the crust may have been almost wholly downward, change from sea to land being effected by sedimentation. The assumption that large parts of the

continental areas were many times evenly raised and lowered several hundreds of feet is much less reasonable than that the vertical movements of the crust were small and perhaps mainly movements of sinking only. Thus, the observed alternation of marine and nonmarine formations in the Pennsylvanian stratigraphic column favors the conclusion that the average depth of the seas was slight (possibly less than 100 feet).

Some leading geologists have held that the gentle dip of the Pennsylvanian strata is original. For example, the nearly uniform westward inclination of these beds in the Mid-Continent region (about 0.5 degree in Kansas, 1.5 degrees in south central Oklahoma) approximately repre-

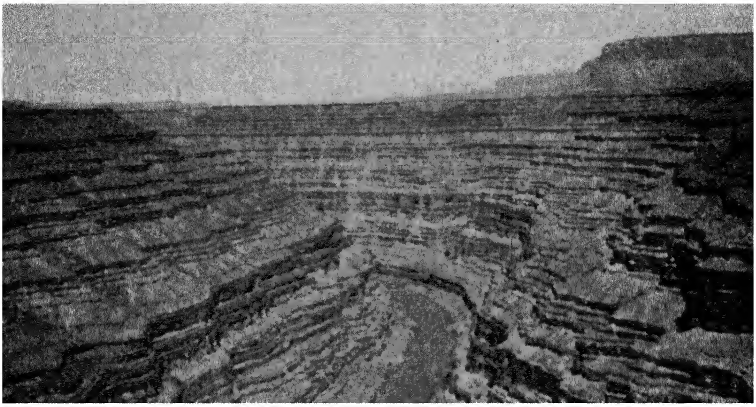


FIG. 157.—Pennsylvanian limestones, sandstones, and thin shales (Goodridge formation), about 1,325 feet thick, in the canyon of San Juan River, southeastern Utah. (*R. C. Moore.*)

sents the slope of the Pennsylvanian sea bottom according to this view. If this is true, however, we must conclude that the sea was 4,000 or more feet deeper in the west than in the east, since the beds are traced by means of well borings to at least this much below the outcrop elevations. The presence of nonmarine formations at similar depths below the outcrop can only mean, on the initial-dip hypothesis, that the sea level was lowered thousands of feet. Marine strata above the nonmarine, both continuous from the outcrop to great depth, require a corresponding great rise of sea level. The number of alternations in kind of deposits and their deeply interfingered relations render entirely untenable the hypothesis that these beds were laid down in their present attitude. Taking into account, also, the evidence of fossils and of lithology, we may say confidently that the Pennsylvanian epicontinental seas were probably nowhere thousands of feet deep and that vertical shifting of the strand line was never of this order. We may conclude, rather, that the seas were shallow, that vertical movements of the strand line were small, that the original attitude of the beds was practically horizontal, and that the present dip of the rocks is due to a later regional tilting.

Thickness.—The thickness of the Pennsylvanian deposits ranges from 1,000 or 2,000 feet in parts of the interior region of the continent to more than 25,000 feet in the Ouachita geosyncline of Oklahoma and Arkansas. Post-Paleozoic erosion has removed a large part of the Pennsylvanian deposits in most of the Appalachian region, but in places the remaining beds are more than 10,000 feet thick. Thicknesses of Pennsylvanian formations totaling several thousand feet are also reported from the Cordilleran geosyncline.

Coal

The subject of coal holds a prominent place in economic geology because of its commercial importance, but it is also of much interest in

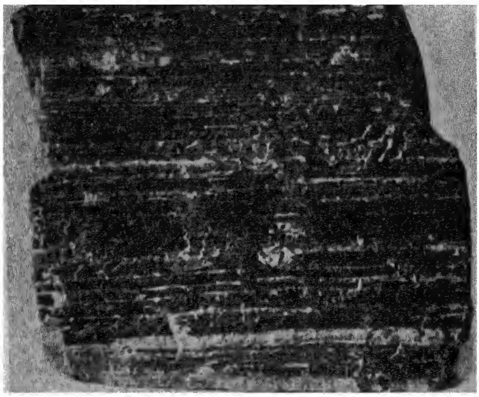


FIG. 158.—Block of coal from the Pittsburgh bed of western Pennsylvania. This coal consists of innumerable thin shiny streaks consisting of slightly altered woody plant tissue (*anthraxylon*), and of equally thin dull, lighter-colored layers of decomposed plant matter of various sorts (*attritus*). Slightly less than natural size. (*R. Thiessen, Illinois Geol. Survey.*)

historical geology because of the special physical conditions that are involved in making it. Coal occurs in rocks of all ages from the Devonian to Recent. Discussion of the conditions of coal formation is most appropriate here, however, because the Pennsylvanian, or Upper Carboniferous, is the chief coal-bearing system in the geologic column. Study of the formation of coal involves (1) examination of the physical and chemical characters of coals, and (2) observation of geologic features of coal beds.

Nature of Coal.—From the standpoint of physical properties, coal may be described as a moderately hard, black rock, homogeneous or with banded shiny and dull streaks, and breaking easily or with difficulty, with even or uneven fractured surfaces. Some coal breaks down into small pieces (slacks) when exposed to the air, but other kinds remain

the same almost indefinitely. Some coals ignite easily, others with difficulty. Some burn with a yellowish flame and much smoke, others with a bluish flame and little or no smoke. Some have a low heating capacity (commonly expressed in B. t. u., British thermal units) and others a high value. These physical differences in coals are associated with terms indicating grade, such as lignite, bituminous coal, and anthracite. They are the result of differences in the conditions of formation of the coal-making substances, of subsequent physical alteration, or of both.

Chemical analyses show that coal consists mainly of carbon with smaller, but important quantities of hydrogen and oxygen and also, with much variation, small quantities of sulphur, aluminum, silicon, and other elements. The low-grade coals contain the largest proportion of hydrogen and oxygen in relation to carbon, whereas the high-grade or anthracite coals show a relatively low content of hydrogen and oxygen and a very large proportion of carbon. The percentage of noncombustible mineral matter varies greatly, being least in the very pure coals and increasing in impure coals to a quantity exceeding the combined carbon, oxygen, and hydrogen. As a matter of fact, there is no line of demarcation between impure coal and carbonaceous shaly deposits in which noncombustible material exceeds the combustible.

Geologic Characters of Coal Beds.—Coal beds are commonly found interbedded with sandy or shaly strata, but in some cases marine limestone occurs directly above or below a coal deposit. The fact that coal beds are characteristically associated with continental formations and are indeed essentially restricted to them is significant as to the environmental conditions under which coal is formed. Coal beds vary in thickness from a fraction of an inch to several tens of feet locally. Some beds are not extensive horizontally, but others are traced hundreds of miles along the outcrop and are known to be continuous over areas of many thousands of square miles. Very commonly the bed next beneath a coal is a plastic clay, and in many cases the strata just above a coal contain abundant well-preserved leaves and other remains of land plants.

Formation of Coal.—The chemical nature and geologic association of coal beds furnish basis for the inference that coal is composed of the remains of land plants. Indeed, some coals contain clearly identifiable leaves, flattened twigs or branches, and other marks of land vegetation that can be seen with the unaided eye. The technique of coal study by means of thin sections, polished sections, and etching permits definite recognition of plant tissues of various sorts in practically all coals, even in anthracite, which has undergone most profound change from the original plant material. There is, then, no slightest room for doubt as to the plant origin of coal. But we must ask how the plant materials are

accumulated in the necessary quantity and purity and how they are preserved and altered to make coal.

The accumulation of any appreciable quantity of plant matter requires that addition of plant substance exceed loss by removal or by chemical decomposition. The only places on existing land where this sort of an accumulation is being formed is in swamps, marshes, or shallow lakes, where the plant material on falling is prevented from rapid and complete decay by a protecting cover of water. On dry land, leaves and wood gradually rot and disappear. That most coal beds are formed by vegetation growing where the coal is found is indicated by the presence of standing stumps in coal beds, by marks of roots penetrating the clay beneath coal beds, by the purity of the coal (for, if transported, much sediment would be admixed with the vegetable matter), and in many cases by abundant well-preserved plants of delicate nature in shale above the coal beds.

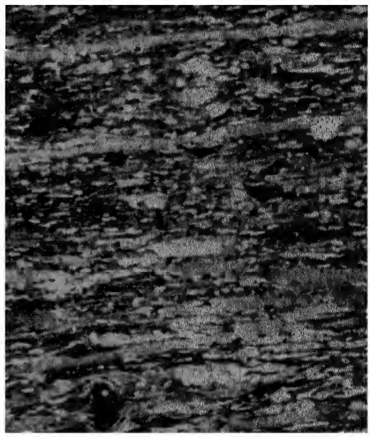


FIG. 159.—Thin section of Pittsburgh coal at right angles to bedding. This shows numerous spore cases (small white bodies), thin layers of attritus, and waxy, resinous bodies (enlarged about 135 ×). (*R. Thiessen, Illinois Geol. Survey.*)

While decay of plant matter is retarded under water, it is not completely stopped, for the action of bacteria partly breaks down cells and modifies the chemical nature of the plant substance. If these biochemical changes proceed far enough, the entire structure of the wood or other plant matter may be destroyed, leaving a dark gelatinous substance. Commonly, however, a considerable part of the original cell structure, especially of the more resistant parts of the plants, is preserved. The deposits formed by this accumulation and partial chemical change are called peat.

The conversion of peat to coaly material is accomplished by slow chemical and physical changes in which compression and heat are the important causal factors. Oxygen and hydrogen are progressively given off, leaving a residual concentration of carbon. Thus peat is converted to lignite, and lignite to bituminous and anthracite coal, or, in case of extreme compression and heating, to graphite, which consists of pure carbon. These relations are illustrated in the change of character of coal beds (1) from higher to lower horizons, the latter having a greater carbon concentration because of the effect of weight of greater thicknesses of overlying sedimentary rocks, and (2) from regions of undisturbed

rock formations to those in which the strata have been folded by mountain-building. Thus, coal that has been buried by 5,000 feet of strata should have a somewhat higher carbon ratio than coal buried by 1,000 feet of rocks, and the coal in the nearly flat-lying formations of western Pennsylvania should be "softer" (containing more volatile hydrocarbons) than that of the folded rocks of eastern Pennsylvania. Observation accords with these expectations. Extreme compression of coal-bearing strata in Rhode Island has produced graphitic coal with so little remaining oxygen and hydrogen that it can hardly be burned.

FIG. 160.—A modern cypress swamp in Virginia. Except for differences in the kind of plants, it is probable that this represents the sort of environment in which the Pennsylvanian coal beds originated. (*L. W. Stephenson, U. S. Geol. Survey.*)

The occurrence of several coal beds in a single stratigraphic column shows repeated existence of swampy, coal-forming conditions in the area considered. Where marine strata overlie a coal, we may easily understand that the swamp vegetation was drowned by sinking of the land or a rise of the sea level. Eventually when sedimentation had largely displaced the water, a new coal swamp could be established. Similarly the rapid spreading of silt and sand by streams might so change conditions in marshy, ill-drained areas as to bring the formation of coal to an end. The Pennsylvanian system is characterized by the remarkable number and almost incredibly large geographic distribution of coal beds.

PENNSYLVANIAN FORMATIONS OF NORTH AMERICA

Distribution

Exposures of Pennsylvanian rocks are widespread in the eastern part of North America in (1) the Appalachian region, extending from New York to Alabama, (2) New England and the maritime provinces of

Canada, (3) Michigan, and (4) the Eastern Interior region, including parts of Illinois, Indiana, and western Kentucky. Outcrops are extensive also in (5) the Mid-Continent region, including parts of Iowa, Nebraska, Missouri, Kansas, Arkansas, Oklahoma, and Texas, and (6) in many portions of western North America.

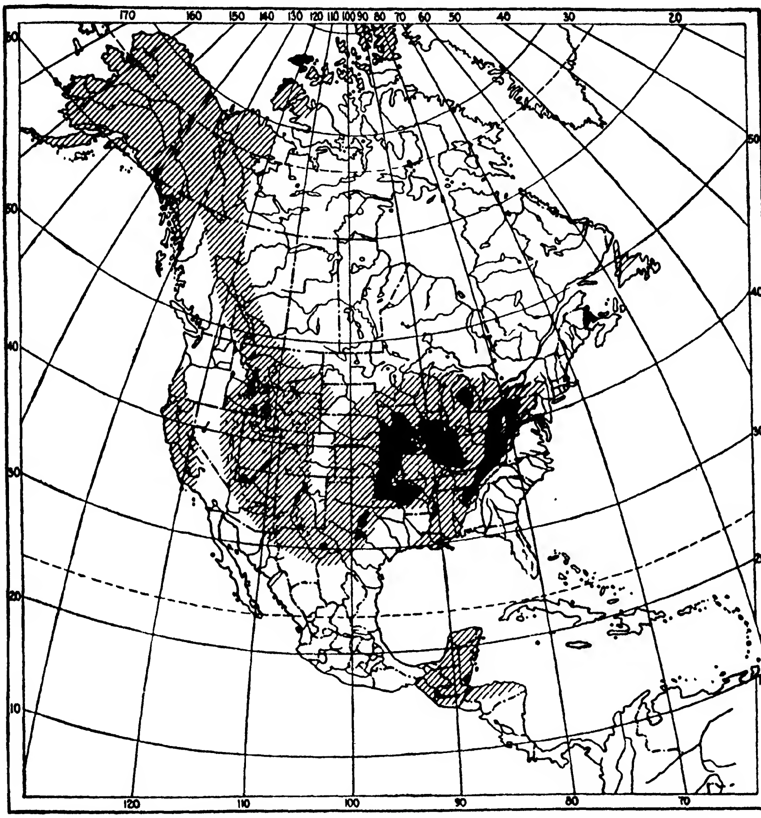


FIG. 161.—Map of North America showing outcrop areas of the Pennsylvanian system (black) and the inferred area of original distribution of Pennsylvanian formations (oblique shading). (*J. M. Weller, in Chamberlin and Salisbury's Historical Geology, Henry Holt & Company.*)

The distribution of Pennsylvanian rocks as shown on a geologic map of the continent shows some points of contrast with that of older Paleozoic systems. The latter appear at the surface in belts of varying width between outcrops of older and younger rocks. The Pennsylvanian, on the other hand, is the youngest system (excepting Quaternary) that is present in some large districts, and therefore the rocks of this age occur in broad areas without cover of younger strata. The large rounded outcrop areas of the Pennsylvanian in the Eastern Interior region and Michigan represent very broad shallow basins or synclines filled by Pennsylvanian formations and surrounded by older Paleozoic rocks.

The Appalachian district shows the same relations except for a small patch of Permian that overlies the Pennsylvanian in part of the north and for the overlap of Mesozoic beds at the southern end. The Mid-Continent and western Pennsylvanian outcrop areas, however, are bordered on one or more sides by younger formations, and there are large areas where the Pennsylvanian system occurs at varying depths below the surface but is concealed.

Classification

Because of the lack of sufficient general knowledge, a different classification of the Pennsylvanian rocks has been employed in each of the outcrop areas and even in parts of a single district.

The section in Pennsylvania and other parts of the Appalachian district was early divided into four parts: in upward order, Pottsville, Allegheny, Conemaugh, and Monongahela. These are based primarily on lithology and the distribution of coal beds, the first and third containing much less coal than the second and fourth. It may be noted, however, that in the central and southern Appalachians the Pottsville is a very important coal-bearing series. The boundaries between the so-called series are arbitrarily selected coal beds.

The Pennsylvanian of the Eastern Interior region is divided into formations that for the most part are bounded by arbitrarily selected coal beds. Correlation with the Appalachian district is made on the basis of comparison of lithology and fossils.

Pennsylvanian rocks of the northern Mid-Continent have been divided into two series (Des Moines, Missouri) composed of seven groups of formations, but in Oklahoma and Arkansas an entirely different classification has been used. In Texas there are four series: in upward order, Bend, composed largely of limestone; Strawn, thick shale and sandstone; Canyon, containing prominent limestone beds; and Cisco, made up of alternating thin beds of limestone, shale, sandstone, and conglomerate.

Local formation names are applied to the Pennsylvanian of the west.

It is evident that any generally applicable subdivision of the Pennsylvanian rocks of North America should have maximum significance in terms of physical history. The essential basis of this kind of subdivision is diastrophism, which is recorded geologically by deformation of beds, occurrence of unconformities, changes in lithologic character of deposits, and modifications of faunas and floras.

The Appalachian section, which has commonly been regarded as a type for the Pennsylvanian, is not divided on the basis of diastrophism and, because of the unimportance of fossil-bearing marine deposits and poorly defined evidence of crustal disturbances during the period, is not the best standard for the system.

The Mid-Continent region, on the other hand, contains a succession of deposits that is admirably fitted to serve as a standard for comparison with Pennsylvanian formations of other parts of the continent. The rock formations are well exposed, and in addition there is information from about 200,000 deep wells. The geologic structure is mostly very simple. Highly fossiliferous marine beds alternate with nonmarine strata, lithologic characters of different parts of the stratigraphic column being differentiated broadly according to conditions of relative crustal stability or of instability accompanied by local mountain-building. At certain horizons there are important unconformities and changes in fauna which afford a natural basis for subdivision of the Pennsylvanian. Therefore, we shall define the epochs of Pennsylvanian time on the basis of conditions observed in the Mid-Continent. Ultimately, it is probable that these divisions will be recognizable in the Pennsylvanian sections of other parts of the continent. There are four major natural divisions, or series,

that are thus recognized in the Pennsylvanian system, each representing a chapter in the record of the physical history of the period. The series are designated, in upward order, (1) Morrow, (2) Des Moines, (3) Missouri, and (4) Virgil. Their characters will be described in the paragraphs devoted to the Mid-Continent region.

Appalachian Region

Rocks of Pennsylvanian age in the Appalachian region occur almost entirely west of the belt of mountain folding. They extend from southwestern New York through Pennsylvania, western Maryland, West Virginia, eastern Ohio and Kentucky, southwestern Virginia, eastern Tennessee, and northwestern Georgia, into Alabama. The strata of this region are in general nearly flat-lying or only gently folded, and the presence of hard sandstones forms an upland country, the Appalachian Plateau. Exception to the conditions that prevail in most of this district appears in northeastern Pennsylvania and near Birmingham, Ala., where the Pennsylvanian beds are involved in strong folding. The steeply upturned Pennsylvanian rocks of the anthracite district or basin in northeastern Pennsylvania have been isolated by erosion from the main Pennsylvanian area to the west, the outlying remnants being merely the lower parts of steep synclines. Despite the synclinal structure of the anthracite district formations, the rocks are very prominent topographically because upturned beds of hard conglomerate and sandstone form mountain ridges that enclose the coal basins.

General Characters.—The Pennsylvanian deposits of the Appalachian region consist predominantly of shales and sandstones. Conglomerates are prominent, especially in the lower part of the system and in the eastern and southern portions of the outcrop area. Coal beds are numerous and of great economic importance. Limestones are common, except in the lowest series (Pottsville). The limestones of the Allegheny and Conemaugh series are mostly thin, marine beds, some of which are traceable for long distances. Those of the Monongahela series are nonmarine and in general much thicker.

Correlation of beds in different parts of the Appalachian district has been based on (1) detailed mapping, in which certain coal beds, a few massive prominent sandstones, and some limestones have been traced for many miles, (2) studies of marine fossils, chiefly in the northwest part of the area, and (3) investigations of fossil plants.

Pottsville Series.—The oldest part of the Pennsylvanian, comprising the Pottsville series, is exposed at the margins of the Appalachian Pennsylvanian area from New York to Alabama. Practically all of the Pennsylvanian rocks south of West Virginia belong to the Pottsville series. Younger rocks may once have been present in this southern region, but if they were they have been removed by erosion. The Pottsville rocks rest everywhere on eroded Mississippian formations.

Near the town of Pottsville, in eastern Pennsylvania, these rocks are about 1,300 feet thick. They consist of sandstone, shale, thin coal beds, and much conglomerate, especially in the upper part. The pebbles are mostly fairly well-rounded pieces of quartz about an inch in average diameter, but some of them are as much as 6 inches across. Westward, the thickness and coarseness of the Pottsville beds decrease very markedly and beds containing marine fossils appear. There are 13 fossiliferous marine horizons in the Pottsville of eastern Ohio. In western Pennsylvania the series is only 100 to 200 feet thick and consists of two medium-grained sandstones separated by shale-containing thin coal beds.

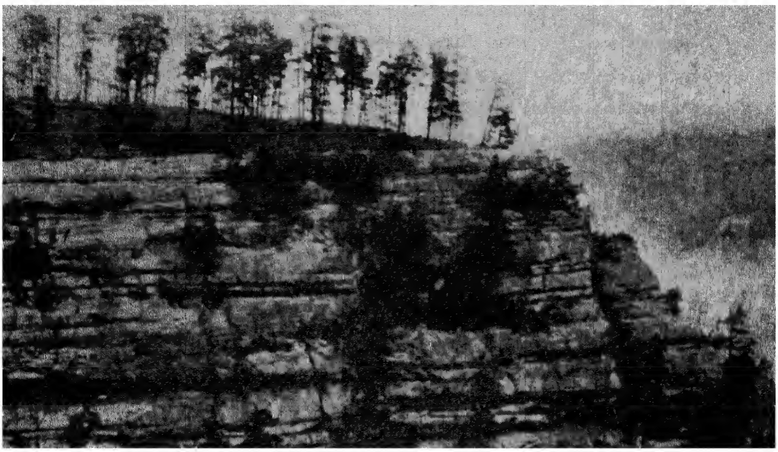


Fig. 162.—Massive Pottsville conglomerate and sandstone, Powell County, east central Kentucky. (*W. R. Jillson, Kentucky Geol. Survey.*)

As the rocks of Pottsville age are traced southward, the thickness is found to increase gradually to about 6,000 feet in southwestern Virginia, and to more than 9,000 feet in Alabama (estimated original thickness about 10,500 feet). The southern Pottsville, like that in eastern Pennsylvania, is mainly nonmarine and contains a great deal of sandstone and conglomerate, the latter containing pebbles of quartzite and chert up to 6 inches in diameter. These coarse materials are evidently stream-borne and were probably deposited in the form of large alluvial fans built outward to the west and northwest from uplands that lay southeast of the area of sedimentation. They may have been deposited with moderate rapidity. There is much coal, however, in the central and southern Appalachian region, and the accumulation of plant matter to make coal beds is relatively slow. The most important Pottsville coal fields occur in southern West Virginia, southwestern Virginia, eastern Tennessee, and Alabama. The West Virginia and Virginia section contains about 50 different coal beds, among them the well-

known Pocahontas coal which is extensively used in eastern markets. The Pottsville rocks, in basins east and west of Birmingham, contain 40 coal beds, of which 11 are mineable.

An interesting feature of the Pottsville series is a distinct overlap from east to west. The oldest known Pottsville beds (Pocahontas group) are confined to the eastern margin of the Appalachian Pennsylvanian area. The next younger Pottsville division (New River group) rests on the Pocahontas but also extends over a large territory farther west where it lies on eroded Mississippian rocks. The youngest Pottsville (Kanawha group) extends still farther westward. The basin was thus gradually filled with sediment, which obviously was derived from the east, as indicated by increasing coarseness and thickness in that direction. The formations are dominantly of continental origin. Fossiliferous marine horizons are few. There is reason to believe that the Pottsville deposits originally extended considerably farther east than the present easternmost outcrops.

Allegheny Series.—The Allegheny beds overlie the Pottsville conformably, the boundary between the series being arbitrarily defined as occurring at the base of a certain coal bed. They occur in Pennsylvania, Maryland, West Virginia, Kentucky, and Ohio. Sandstone and shale, partly marine and partly of continental origin, are the chief kinds of rock, but there are five or six widely distributed mineable coal beds, and a few thin but persistent marine limestones. Beds rich in iron carbonate (siderite) and iron oxide (limonite) occur in many places. The series thus consists of alternating marine and nonmarine sediments. Thickness of the Allegheny series ranges from about 125 to 350 feet, the maximum being found in parts of Pennsylvania. Rocks of this age were probably present originally in the southern part of the Appalachian district but have been eroded away.

Conemaugh Series.—The Conemaugh series, 500 to 900 feet in thickness, occurs in the same region as the Allegheny, but in many places the upper beds have been removed by erosion. The boundaries of the series are arbitrarily selected coal beds. The Conemaugh rocks are similar to the Allegheny beds except that coal is less prominent and several of the shales are red. Several thin but persistent marine limestones and some marine shales alternate with the continental sandstone, shale, limestone, and coal beds. Shale is the most important type of deposit from a quantitative standpoint, but sandstone is also important and is prominent at the outcrop.

Monongahela Series.—The uppermost part of the eastern Pennsylvanian, called the Monongahela series, is confined to West Virginia, Maryland, Ohio, and Pennsylvania. It is about 400 feet thick and is composed mainly of shaly beds. There are several coal beds, the Pittsburgh coal at the base being one of the most important of the beds

mined in the east. The series, including much fresh-water limestone, is almost entirely of continental origin.

New England and Eastern Canada

Rocks of Pennsylvanian age occur in Connecticut, Rhode Island, Massachusetts, New Hampshire, and Maine. They extend northward beyond New England, also, and have been mapped in New Brunswick, Nova Scotia, and western Newfoundland. The Pennsylvanian formations of this entire region are distinguished by (1) prominence of conglomerates, some of which are thick and coarse, (2) complexity of structure, (3) chiefly nonmarine nature of the deposits, and (4) comparative scarcity or, locally, the absence of fossils. The thickness of the system is reported to attain a maximum of about 13,000 feet in this district, but in most places it is much less, owing mainly to effects of post-Pennsylvanian erosion. An unconformity is recognized between Pennsylvanian and Mississippian beds.

The Pennsylvanian rocks of New England and eastern Canada almost certainly represent part of an originally continuous series of deposits extending into the Appalachian region and thence westward into the Continental Interior. The abundance of conglomerates and the coarseness of much of the sandstones in the northeastern district indicate proximity of this area to an upland, evidently located to the southeast, from which the pebbles, sand grains, and finer land waste were derived. The rocks are very poorly stratified in some parts, and moderately well stratified in others. Original characters of the deposits have been obscured or even obliterated by the deformation and metamorphism that have affected them. The beds are steeply folded, the intensity of the folding increasing eastward. Thrust faults occur in places. In some areas the sandstones and conglomerates have been altered to quartzite schists, shaly deposits to phyllites or slates, and coal beds to graphitic coal or graphite. Intrusion of igneous rocks, especially granite, and injections of quartz veins have greatly influenced the Pennsylvanian rocks, so that in much of the New England-eastern Canada district these rocks do not at all resemble the deposits of equivalent age in other areas.

Michigan Basin

The central part of Michigan, which has a symmetrically saucer-like synclinal structure, contains Pennsylvanian rocks about 700 feet thick. These are almost all of Pottsville age. Thick sandstone and quartz pebble conglomerate occur at the base, while next above are shales and sandstones with coal beds and some thin limestones. The Pennsylvanian strata of the Michigan Basin are about 150 miles from the nearest outcrops of similar age which lie respectively to the southeast and south-

west. It is possible that the deposits were partly isolated during the time of their formation, but the occurrence of marine fossils in some of the beds indicates a connection with other Pennsylvanian areas which has subsequently been removed by erosion. It is probable that Pennsylvanian deposits once covered most, if not all, of the territory lying between the Appalachian, Michigan, Eastern Interior, and Mid-Continent regions.

Eastern Interior Region

The Eastern Interior Pennsylvanian area covers most of Illinois and western Indiana and extends a short distance into western Kentucky

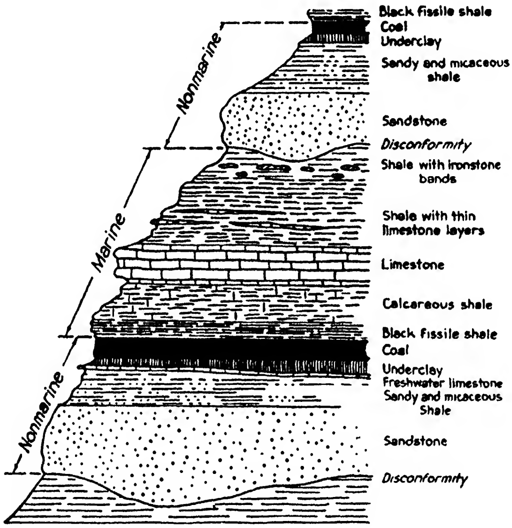


FIG. 163.—Section showing typical relations of coal bed to associated strata in the Eastern Interior basin.

and eastern Iowa. The rocks are almost flat-lying but have actually the form of a very broad, shallow synclinal basin. Accordingly, the oldest formations are exposed near the margins of the Pennsylvanian area, and successively younger beds appear toward the interior of the basin. Because glacial drift covers most of this region, good exposures of the Pennsylvanian strata are few. The total thickness of the Eastern Interior Pennsylvanian rocks is approximately 1,000 feet. Equivalents of the Pottsville, Allegheny, and part of the Conemaugh series are recognized, but the beds are in general thinner and finer, the number of coal beds is smaller, and there is a somewhat larger proportion of marine sediments. The coal is of very good quality and a large part of the coal deposits are of mineable thickness.

Investigations conducted mainly by the Illinois, Indiana, and Kentucky geological surveys have shown that many of the Pennsylvanian

strata in this region are surprisingly persistent. This applies especially to certain limestone, shale, and coal beds, including some stratigraphic units that are only a foot or two in average thickness. The names applied to the same beds differ to some extent, however, in the different states. There are local variations in the thickness of beds, especially in the case of sandstones, some of which very clearly have the form of channel fillings. The succession of various types of sediment in a fairly

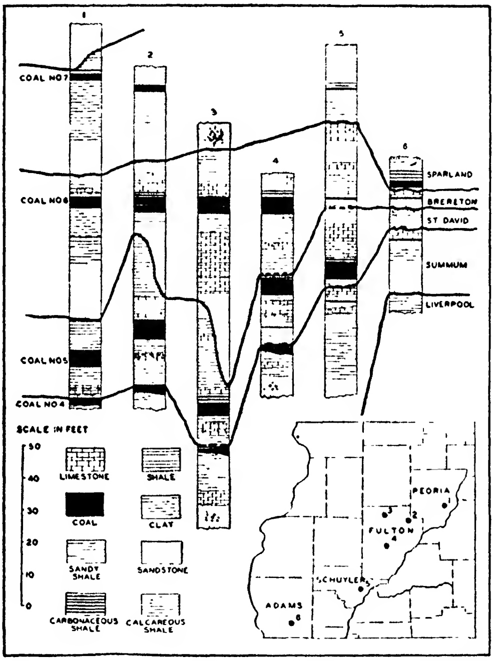


Fig. 164.—Sections of Pennsylvanian beds in western Illinois, showing division into cycles. (*H. R. Wanless, Illinois Geol. Survey.*)

definite order that is several times repeated is an important character of the Eastern Interior Pennsylvanian section.

An interesting structural feature in this region is the La Salle anticline, a sharp-crested, very asymmetrical rock fold that trends slightly east of south from La Salle, Ill., and extends in a nearly straight line for a long distance. The pre-Pennsylvanian rocks dip steeply toward the west, but very gently toward the east. Pennsylvanian deposits cover the anticline and the older rocks unconformably. The fact that older Pennsylvanian formations which are well developed in the basin to the west and on the east flank of the anticline do not extend across the arch, while the later Pennsylvanian is continuous across it, shows that the fold was formed before the time of Pennsylvanian sedimentation. As these sediments accumulated, there was less and less of the anticline left uncovered, and finally it was entirely buried. The oil and gas fields of Illinois are mainly located on the La Salle anticline. At the time of formation of some of the Pennsylvanian sands that contain the oil, the La Salle anticlinal ridge formed a long straight promontory projecting southward into a shallow sea where the sand bodies were deposited as spits and bars.

Mid-Continent Region

The Mid-Continent region contains one of the most complete and clearly decipherable records of the Pennsylvanian period to be found in North America. Outcrops of Pennsylvanian formations extend from Iowa to Texas. They occupy almost all of northwestern Missouri, the southeastern part of Nebraska, the eastern one-fourth of Kansas, eastern Oklahoma, west central Arkansas, and a part of north central Texas. The Pennsylvanian strata dip westward at an average rate of about 25 to 40 feet per mile, disappearing beneath younger formations, and by means of well records are known to underlie most of the plains country east of the Rockies. The Pennsylvanian outcrops of the Mid-Continent region are therefore only the eastern part of a much larger area of Pennsylvanian sedimentary rocks.

The aggregate thickness of the Pennsylvanian in the northern part of the Mid-Continent region is 2,000 to 3,000 feet. Southward there is a gradual increase in thickness to about 25,000 feet in eastern Oklahoma and west central Arkansas. The total thickness of the Pennsylvanian in Texas is a little over 5,000 feet.

The general nature of the Pennsylvanian strata of eastern Kansas and adjacent parts of the northern Mid-Continent and of north central Texas is essentially the same. The outstanding characters are the relative importance of marine strata, extreme persistence and lateral uniformity of most of the stratigraphic units, and the occurrence of many comparatively thin formations of alternating shale, limestone, sandstone, and a few coal beds. The hard beds, chiefly limestone, form prominent north-south trending escarpments with steep east-facing fronts and gently inclined back slopes. Weak rocks occur along the lower part of escarpments and form lowlands between them.

The Pennsylvanian territory in central and southern Oklahoma and west central Arkansas differs in several respects from that of country to the north and south. Marine strata are less prominent, the thickness of the formations is much greater, sandstone and shale greatly predominate over limestone, conglomerate occurs at many horizons, and there are red beds of continental origin, especially toward the top of the section. In much of the region the rocks are steeply folded, the sandstones forming ridges that are thickly forest-covered. Unconformities within the Pennsylvanian are prominent near the southern Oklahoma mountain uplifts, but, though traceable for long distances, they become inconspicuous away from the uplifts.

Morrow Series.—The oldest Pennsylvanian rocks of the Mid-Continent region consist of dark-colored marine shale and limestone containing a distinctive fauna that is related to that of Upper Mississippian rocks, on the one hand, and to the succeeding Pennsylvanian, on the

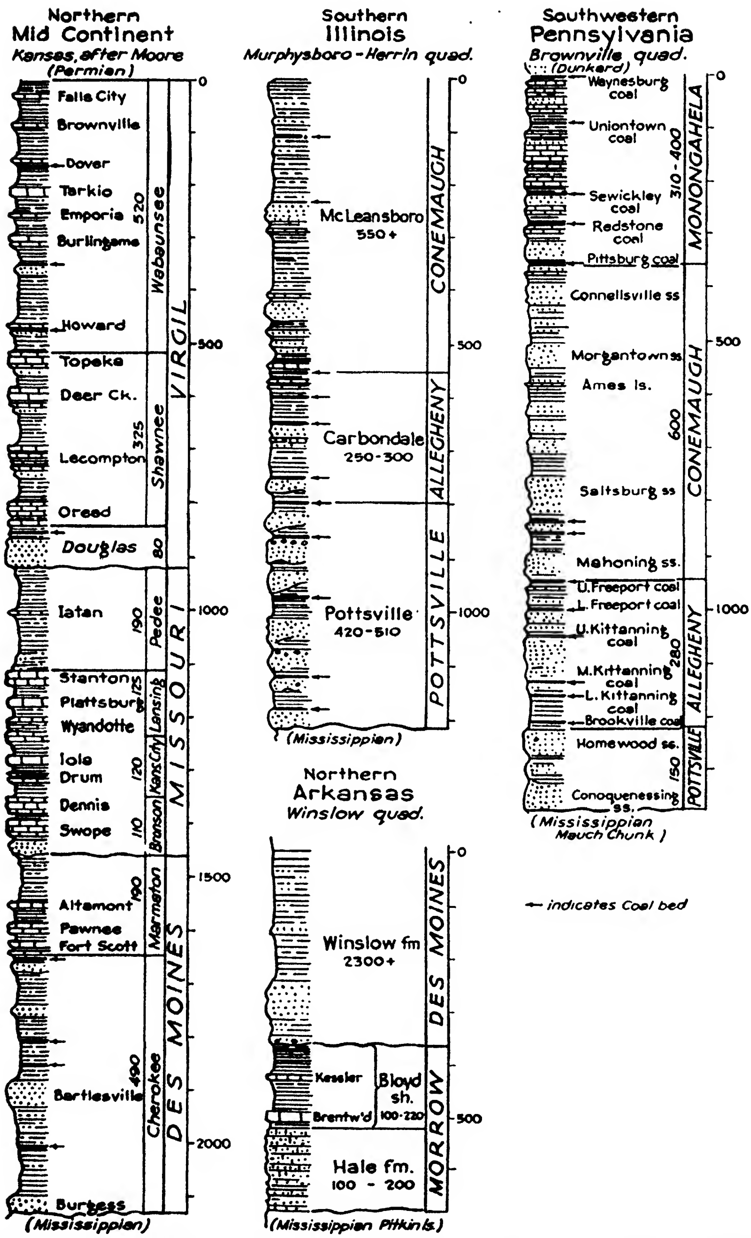


Fig. 165.—Generalized sections of the Pennsylvanian system in the northern Mid-Continent, Arkansas, Illinois, and Pennsylvania.

other. Outcrops occur on the southwest flank of the Ozarks in northwestern Arkansas and northeastern Oklahoma, on the south and northeast sides of the Arbuckle Mountains in southern Oklahoma, north of the Ouachita Mountains, and in the Llano region of central Texas. The Morrow strata rest unconformably on Upper Mississippian rocks and locally in central Texas overlap on to Lower Ordovician rocks.

The average thickness of the Morrow series is about 1,000 feet, but north of Ardmore, Okla., the beds assigned here (Springer and lower Dornick Hills formations) have a total thickness of about 4,000 feet. In central Texas there is 300 to 600 feet of solid limestone (Marble Falls) which is clearly of Morrow age, and this is overlaid by about 400 feet

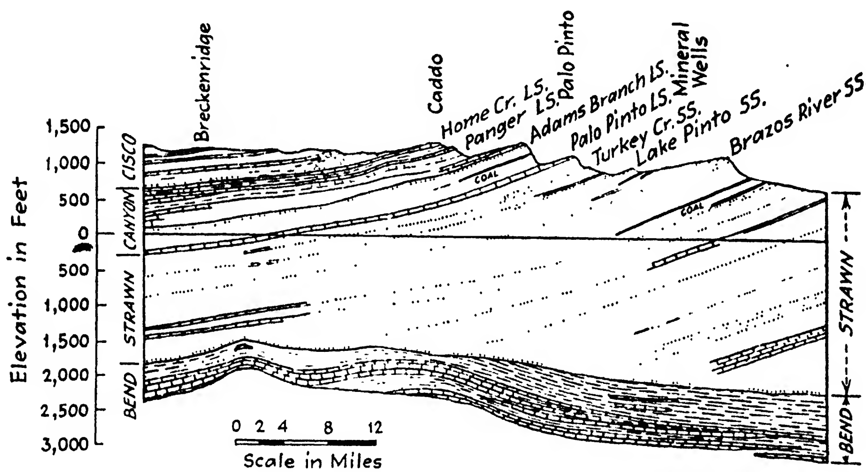


FIG. 166.—Geologic section of Pennsylvanian rocks in north central Texas showing the great discordance in structure of the Bend and Strawn series. (*F. B. Plummer, University of Texas.*)

of black shale and some limestone (Smithwick) that appears also to belong to the Morrow series. Conditions of sedimentation in Morrow time were evidently rather uniform, and there were no adjacent highlands from which coarse sediments could be supplied. The duration of the epoch was moderately long, as judged by the considerable thickness of limestones and fine black muds that were deposited in certain places.

Post-Morrow Unconformity.—The Morrow series is separated from succeeding Pennsylvanian strata in the Mid-Continent region by an important unconformity. This unconformity is conspicuous in some places.

Bend Arch.—North of the Llano Uplift in Texas the rocks of Morrow age have the form of a broad anticline or arch that plunges gently northward. This is known as the Bend Arch, a structural feature that largely controls oil production from the Marble Falls and Smithwick formations. Weathering of the limestone that preceded deposition of the overlying Pennsylvanian rocks formed many cavities which have served subsequently as a reservoir for accumulation of the petroleum. The post-

Morrow formations show a distinct overlap from east to west, which means that sedimentation was resumed first in the east and later covered portions of the Morrow rocks farther west. Locally the Marble Falls and Smithwick are directly overlaid by Upper Pennsylvanian strata. The unconformity which is thus evidenced is an important one, being indicated by differences in structure of the beds above and below the break, by the weathering of the rocks of Morrow age, by evidence of fossils, and by the sudden change in the nature of the sediments from limestone and fine shale to coarse sands.

Wichita-Criner Folding.—The Wichita Mountains of southwestern Oklahoma are comparatively unimportant as surface features, but under cover of Pennsylvanian and Permian rocks they extend westward across the Panhandle of Texas (the western buried part being known as the Amarillo Mountains) and southeastward into northern Texas (part of the buried eastern end of the mountain chain being known as the Red River Uplift). The Criner Hills, southwest of Ardmore, Okla., consist of faulted and folded Ordovician and younger Paleozoic rocks comprising part of the Wichita system. Observations show the presence of (1) Morrow strata conformable in structure with older rocks, (2) post-Morrow Pennsylvanian beds resting unconformably on deformed and eroded older Paleozoic rocks, and (3) coarse conglomerates (Bostwick) in beds just above the strata classed as Morrow. These prove that mountain-making crustal movements occurred in this part of Oklahoma during the early part of the Pennsylvanian period.

Ouachita Folding.—Occurrence of folding in the Ouachita Mountains region in post-Morrow time is indicated by the presence of chert conglomerates derived from the Ouachita area or its southward continuation in Texas in rocks (Atoka-Strawn) next younger than the Morrow. To be mentioned also is the existence in the western Ouachitas of many large boulders of Ordovician limestones and other rocks embedded in basal Pennsylvanian shale. Some of the boulders are of huge size, up to 369 feet in length by 250 feet in width. Their origin is not known. It is thought by some that icebergs derived from mountain glaciers transported them, and by others that thrust-faulting followed by erosion produced them. It is significant that they occur at about the same geologic horizon in the Ouachita Mountains region and in the Marathon district of western Texas. They appear to indicate existence of mountains, and possibly of crustal deformation, in this early part of Pennsylvanian time.

Nemaha Uplift.—Drilling in Nebraska, Kansas, and northern Oklahoma has brought to light the existence of an important uplift composed of pre-Cambrian granite and pre-Pennsylvanian Paleozoic formations. This uplift, known as the Nemaha Mountains, trends slightly west of south from a point near Omaha, Nebr., extending entirely across Kansas and reaching southward in Oklahoma at least to Oklahoma City. The uplift is entirely buried by Pennsylvanian and Permian strata. The fact that Mississippian rocks are upturned on the flanks of this uplift shows that the crustal movement occurred at a time subsequent to the making of these Mississippian rocks. No strata of Morrow age are known in this region, but the occurrence of slightly younger Pennsylvanian beds (Cherokee) resting unconformably on the eroded rocks of the Nemaha Uplift determines the date of movement as preceding the formation of these Early Pennsylvanian sediments. It is thought probable that the elevation of the Nemaha Mountains may be part of the post-Morrow disturbance.

Des Moines Series.—The Pennsylvanian beds called Des Moines consist almost entirely of sandstone and shale in the central Mid-Continent region, but in the north and to some extent in the south there are persistent limestones in the upper part. Conglomerates occur in places at the base. The deposits attain maximum thickness, about

18,000 feet, in eastern Oklahoma and western Arkansas. In this district, sandstone is much more prominent than any other kind of sediment, but toward the top there is an increasing proportion of shale, and there are some coal beds. The Des Moines series thins rather rapidly northward but is well developed in northwestern Arkansas and throughout the northern Mid-Continent region. The average thickness of the Des Moines rocks in the north is about 700 feet. South of the Arbuckle Mountains in Oklahoma, beds belonging to this series have a thickness of about 8,000 feet and in north central Texas 2,000 to 3,500 feet (Strawn).

Division of the Des Moines series into two groups is based on interruption of sedimentation and folding of early Des Moines beds in the

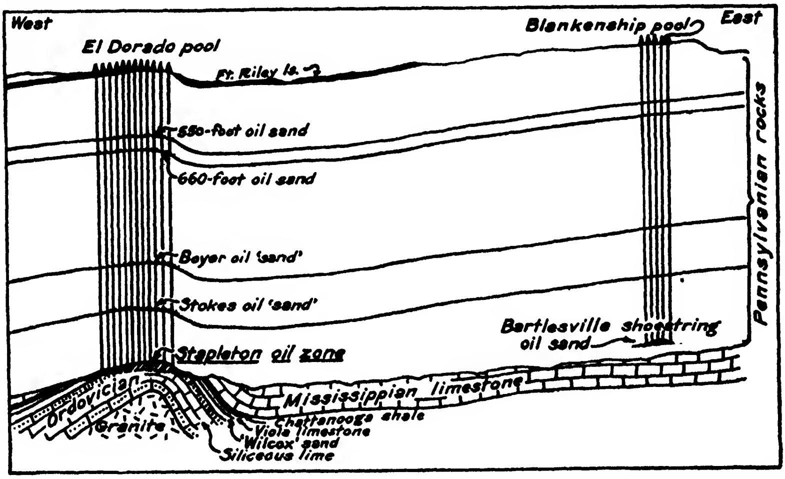


Fig. 167.—Diagrammatic section showing the unconformity at the base of the Pennsylvanian rocks in the vicinity of the buried Nemaha Uplift at El Dorado, Kans. (*R. C. Moore, Kansas Geol. Survey.*)

Arbuckle and Ouachita mountain regions, followed by the spreading of conglomerates at the base of later Des Moines beds and by the local overlap of these on rocks as old as Ordovician. Temporary land conditions in the northern Mid-Continent resulted in the formation of valleys, which were subsequently filled with sand, thus forming part of the "shoestrings" of this region.

Post-Des Moines Unconformity.—Occurrence of a break above the Des Moines series is indicated by local evidences of erosion at this horizon, by a general change from shaly and calcareous deposits to coarse clastic sediments at the beginning of the next following series, and by modification of the marine faunas which make this one of the most clearly defined paleontologic boundaries in the Pennsylvanian.

Missouri Series.—The beds called Missouri series are especially distinguished by the prominence and wide distribution of limestone. This is especially true of the northern and southern parts of the Mid-

Continent, where in places there are 100 to 200 feet of almost solid limestone. Shale is also quantitatively important, especially in the Oklahoma region. Locally at the base are conglomeratic and sandy beds. The thickness of the series attains a maximum of possibly 4,000 feet south of the Arbuckle Mountains in Oklahoma, whereas in the northern Mid-Continent it is only 300 to 500 feet.

Post-Missouri Unconformity.—South of the Arbuckle Mountains, beds of Missouri age and older are steeply folded and in places faulted. This marks the time of main folding in at least the western part of the Arbuckle Range and possibly also in western Texas. The fact that

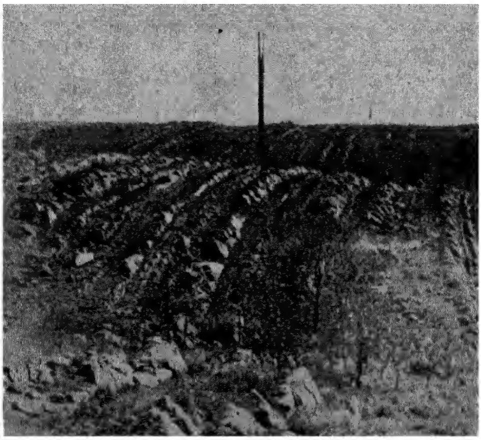


FIG. 108.—Steeply folded Cambro-Ordovician limestone beds in the Arbuckle Mountains, southern Oklahoma. The folding that produced this structure occurred in Late Pennsylvanian time, and the accompanying interruption of sedimentation in the Mid-Continent region defines the boundary between the Missouri and Virgil series. (*R. C. Moore.*)

vertical or steeply dipping Missouri beds are overlaid unconformably by essentially flat-lying later Pennsylvanian strata serves to date the time of the folding fairly precisely. In and near the areas of mountain uplift there are coarse conglomerates that were formed by erosion of the pre-Pennsylvanian rocks. Evidences of the uplift are found also far to the north and south in the occurrence of unconformities and in the conglomeratic or sandy character of the basal portion of the next succeeding series. However, the attitude of the beds above and below the unconformity in these regions at a distance from the mountain-building is parallel.

Virgil Series.—The uppermost beds of the Pennsylvanian in the Mid-Continent region are classed together as the Virgil series. Shale and sandstone predominate quantitatively, but limestone is also prominent. The limestones range in thickness from less than an inch to about 30 feet, and many of the beds are surprisingly uniform and persistent.

In the vicinity of the southern Oklahoma mountains, as already mentioned, there are coarse conglomerates at the base; also there is a considerable hiatus corresponding to beds that occur to the north and south. The conglomerates contain abundant limestone pebbles and cobbles derived from the areas of mountain uplift and locally they overlap on to eroded Ordovician and other pre-Pennsylvanian rocks. Northern Oklahoma and southern Kansas show very prominent sandstones in the lower beds of Virgil age, but these become thinner and locally disappear farther north. Similarly in northern Texas there are prominent sandstones and conglomerate beds which become much thinner southward. Nonmarine red beds are prominent in southern Oklahoma. The total thickness of Virgil strata ranges from about 1,300 feet in northern Oklahoma to about 700 feet in Nebraska.

The upper boundary of the Virgil series and of the Pennsylvanian system in the Mid-Continent region is rather arbitrarily drawn at a certain horizon at which fossils and sedimentary features regarded as characteristic of the Permian first make their appearance.[1] This part of the section appears to be entirely conformable.

West Texas.—The trans-Pecos portion of western Texas may be classed geographically with the Rocky Mountain and western states, but geologically this territory is so closely linked to the Mid-Continent region that it is better considered as a southwestern extension of the Mid-Continent. Pennsylvanian rocks occur in the Marathon district of the Glass Mountains and in the Hueco Mountains. Recent studies show the presence of a very thick Lower Pennsylvanian section of dark shaly and sandy sediments followed by thick limestone and shale (Gaptank) that is of Medial and Late Pennsylvanian age. An important observation is the greatly deformed attitude of the Pennsylvanian rocks as compared with the overlying Permian strata. The Pennsylvanian and older rocks are steeply folded and are affected by great thrust faults. Locally the order of stratigraphic succession is inverted, the beds having been tipped far beyond the vertical. Nearly flat-lying Ordovician rocks are reported above Devonian which in turn rests on overturned Pennsylvanian strata. The deformation was evidently profound. A time of mountain-building, indicated by coarse conglomerates in the Gaptank formation, is assigned to the mid-portion of the Gaptank epoch. The great folding and faulting of the Pennsylvanian and older rocks (Marathon disturbance) occurred at the close of Gaptank time, and a very prominent unconformity separates the upper Gaptank beds from the overlying latest Pennsylvanian deposits of the region.

[1] This boundary has been located commonly at the base of the Cottonwood limestone, about 170 feet above the Americus, but recent studies call for revision of the older definition (see Fig. 175, p. 319).

The Pennsylvanian formations of the Glass Mountains are geosynclinal deposits that are probably continuous eastward under cover of Cretaceous rocks with the southward prolongation of the Ouachita geosyncline of Arkansas and Oklahoma. Evidence from deep wells indicates that the geosyncline swings around the southeast side of the Llano Uplift and extends northward to the Ouachitas and westward to the Glass Mountains.

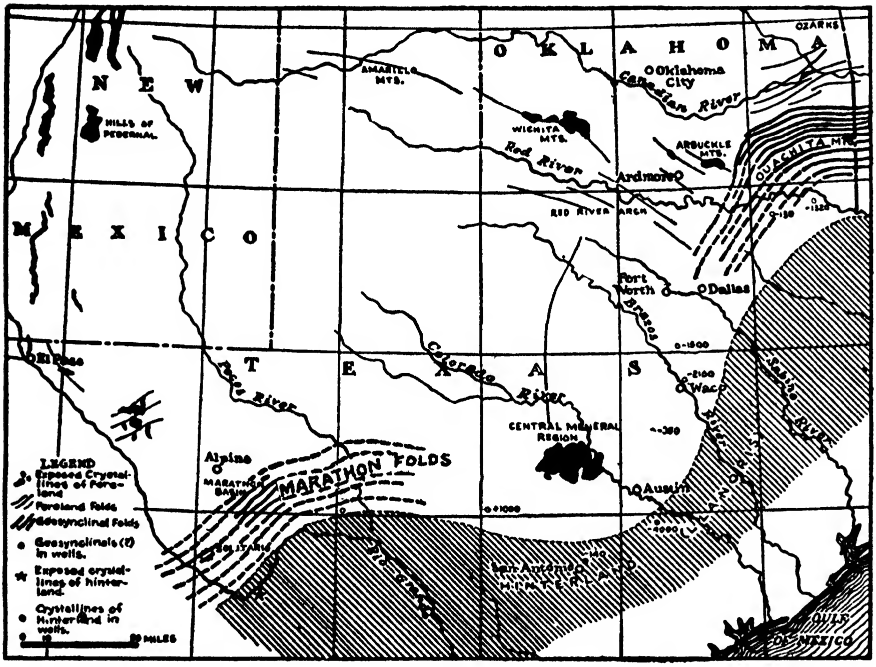


FIG. 169.—Map of the southwestern Mid-Continent region showing relation of axes of folding in the Ouachita geosyncline to the Marathon folds in west Texas. The strike of the Arbuckle, Wichita, and Amarillo Mountains is also shown. (*P. B. King, Texas Bur. Economic Geol.*)

Western North America

Outcrops of Pennsylvanian rocks, mostly of small areal extent, are widely distributed in western North America. They occur chiefly on the sides of mountain uplifts. Alternating beds of hard bluish limestone and light-colored, in many cases feldspathic, sandstone are characteristic of the lower part of the Pennsylvanian deposits. In general, there is a surprisingly small amount of shale. The deposits are mainly marine, so it is evident that the western part of the continent was covered by extensive Pennsylvanian seas. Fossils are abundant in some beds. Sandstone and in places thick deposits of red beds are characteristic of the upper part of the western Pennsylvanian. There is a well-marked unconformity at the base of the Pennsylvanian, but, as in the Mid-

Continent, question exists in many places as to the line of division between Pennsylvanian and Permian strata.

New Mexico.—Pennsylvanian rocks are very widespread in New Mexico. They are divisible into a lower group, about 1,500 feet thick, consisting of hard bluish limestones and dark shales, and an upper group, about 2,000 feet thick, made up largely of red beds. There are some limestones and gypsum deposits in the upper division.

Colorado.—East of the Rocky Mountain Front Range, as well shown near Colorado Springs, the Pennsylvanian deposits consist almost wholly of red and gray sandstone and conglomerate. Central Colorado contains somewhat similar Pennsylvanian beds that are several thousands of feet in thickness. Marine shales, limestones, and sandstones that are gray or dark occur in the lower part of the section, and red beds in the upper part.

The Pennsylvanian lies disconformably on massive Mississippian limestone in most places, but near the mountain uplifts the Pennsylvanian may be found overlapping the older Paleozoic formations and resting

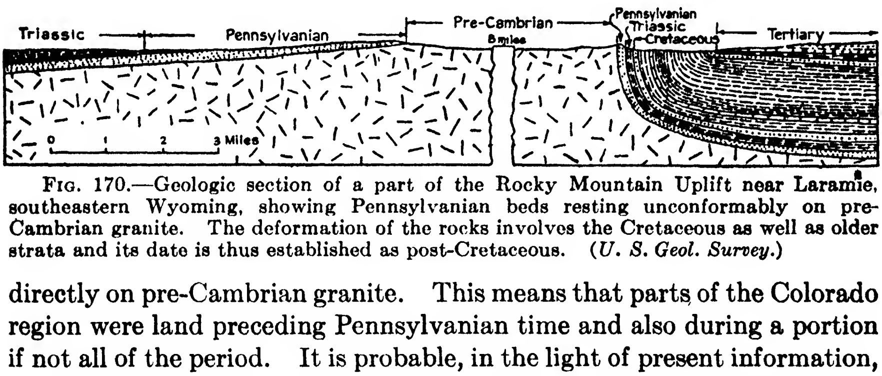


Fig. 170.—Geologic section of a part of the Rocky Mountain Uplift near Laramie, southeastern Wyoming, showing Pennsylvanian beds resting unconformably on pre-Cambrian granite. The deformation of the rocks involves the Cretaceous as well as older strata and its date is thus established as post-Cretaceous. (*U. S. Geol. Survey.*)

directly on pre-Cambrian granite. This means that parts of the Colorado region were land preceding Pennsylvanian time and also during a portion if not all of the period. It is probable, in the light of present information, that most of the pre-Pennsylvanian systems were not deposited as continuous sheets across the site of the Rocky Mountain belt, but rather that they were confined to basins on the east and west sides of the uplift. The overlap of the Pennsylvanian rocks indicates a landward encroachment of sedimentation in this region, or, if older Paleozoic rocks were once present in territory where the Pennsylvanian rests directly on granite, the older Paleozoic formations were removed by erosion before the beginning of Pennsylvanian deposition in the areas considered. The coarse texture of many of the Pennsylvanian sandstones, the common presence of fresh feldspar grains in the sandstones, and the occurrence of conglomerates containing granite and quartz pebbles indicate that land areas of granitic rocks were rather strongly uplifted shortly before the time of making these deposits. Locally, as on the flanks of the Sangre de Cristo Range, granite boulders up to 6 feet in diameter have been reported in Pennsylvanian conglomerates. The evidences of uplift

that are shown in these features are basis for the inference that an upland or possibly one or more mountainous belts existed in Late Pennsylvanian time on the site of the present Rocky Mountains. The term "Ancestral Rocky Mountains" has been applied to these Pennsylvanian highlands. The axis of the Ancestral Rockies, thus interpreted, trends north and south across central Colorado and extends into New Mexico and Wyoming. The elevated land did not extend eastward much beyond the present Front Range, because deep wells in eastern Colorado and western Kansas have penetrated thick Pennsylvanian limestones and marine shales that were certainly not formed on the shores of a mountainous land.

Southwestern Colorado contains a Pennsylvanian section composed mainly of marine limestones and sandstones about 2,000 feet thick. Red clay shale containing weathered Mississippian cherts occurs at the base of the Pennsylvanian system in this region. It represents the residual material derived from the decomposition of Mississippian lime-

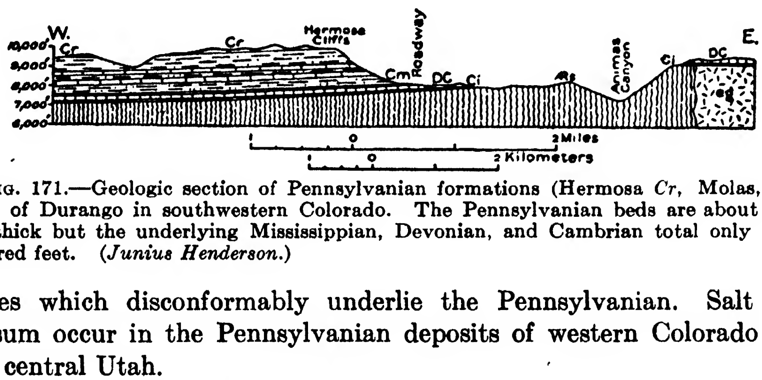


FIG. 171.—Geologic section of Pennsylvanian formations (Hermosa *Cr*, Molas, *Cm*) north of Durango in southwestern Colorado. The Pennsylvanian beds are about 2,000 feet thick but the underlying Mississippian, Devonian, and Cambrian total only a few hundred feet. (*Junius Henderson.*)

stones which disconformably underlie the Pennsylvanian. Salt and gypsum occur in the Pennsylvanian deposits of western Colorado and east central Utah.

Northern Rocky Mountains.—From Colorado the Pennsylvanian formations are known to extend far northward, but they are much thinner than in the central Colorado region. The lower part of the deposits consists of alternating limestone, shale, and sandstone, whereas the upper part is composed mainly of light gray sandstone. The Black Hills of western South Dakota contain a similar succession of beds 400 to 750 feet thick which are classed as a single formation. Outcrops at various places in Montana show about 1,000 feet of Pennsylvanian rocks, the lower part shaly and the upper part a quartzitic sandstone.

Great Basin and Pacific Border.—The eastern part of the Great Basin region, in Utah and Nevada, contains very thick Pennsylvanian deposits, consisting mainly of marine sandstone, limestone, and shale. The total thickness is reported in some places (Oquirrh Range, Utah) to exceed 15,000 feet, but the rocks have been little studied. Southward and northward from the latitude of Salt Lake City the thickness of the system diminishes greatly.

Along the Pacific Border from California to Alaska are scattered outcrops of highly folded and partially metamorphosed Pennsylvanian limestones and calcareous shales in which much igneous material is interbedded. Evidently there was considerable volcanic activity in this region during Pennsylvanian time. The structure of the Paleozoic rocks in the Pacific Border region is so complex and the degree of alteration is so great that information concerning their original characters is difficult to secure.

FORMATIONS OF PENNSYLVANIAN AGE IN OTHER CONTINENTS

Europe.—In Europe, rocks called Upper Carboniferous, which are equivalent to the Pennsylvanian system in America, are very widely distributed and they resemble closely in both lithologic character and fossil content the formations of similar age in the New World. The most important outcrop areas are found in Great Britain, northern France, Belgium, Germany, Spain, the eastern Alps, and Russia. Commonly there is an important unconformity at the base, for in many places the Upper Carboniferous rests on folded and eroded Lower Carboniferous strata, on older Paleozoic, or on pre-Cambrian rocks. As in America, the Permian follows the Upper Carboniferous in most places regularly, the position of the beds being parallel. The thickness of Upper Carboniferous strata is commonly more than 5,000 feet and ranges in places to more than 10,000 feet.

Continental deposits and coal beds are most common and widespread in western Europe. Sandstone and conglomerate are prominent in the lower part of the system, shale and coal especially in the upper part. Conglomeratic sandstone called Millstone grit attains a thickness of 2,500 feet in north central England. The coal beds are numerous, many are of mineable thickness, and some are known to have great horizontal persistence. Part of the coal basin in southern Belgium contains up to 150 different coal beds in a single section about 7,000 feet thick. This shows a truly remarkable recurrence of coal-forming conditions.

The Upper Carboniferous of eastern Europe differs from that in the west in the much larger proportion of marine formations, which show many points of similarity to the rocks of this age in the central and western part of the United States. Limestones with abundant spindle-shaped fusulinids are common and widespread. There are coal beds, however, in parts of the Russian area.

Because of severe compression that affected the Upper Carboniferous rocks, especially toward the middle of this period, the beds are commonly much folded and faulted. In places the strata are overturned. The strike of the strongly folded strata is in general from east to west across western and central Europe, and this defines the trend of prominent mountain chains of Upper Carboniferous time that have been named the Hercynian Mountains or Paleozoic Alps. Igneous intrusions that accompanied the folding are prominent in several districts.

Other Continents.—Marine Upper Carboniferous strata are very widespread in Asia, being essentially a continuation of the formations of eastern Europe. Important outcrops occur in northern China, Manchuria, Korea, the region of the Himalayas, northern India, and parts of Malaysia. Coal beds of great potential value occur in China. A thick section of Upper Carboniferous beds occurs in Australia (Queensland, New South Wales, and Victoria) and rocks of this age are known from southern Africa and also the Sahara region. In South America the Upper Carboniferous is well developed in Peru, Chile, and Brazil, containing both marine and nonmarine strata with coal beds. The presence of Upper Carboniferous formations and coal in Antarctica is indicated by fossils and by outcrops of coal-bearing shale and sandstone.

PHYSICAL HISTORY OF PENNSYLVANIAN TIME

At the beginning of the Pennsylvanian period, North America was broadly emergent but not greatly elevated above sea level. Crustal movements, locally involving mountain-building, had occurred at the close of Mississippian time, the seas had been withdrawn, and erosion was prevalent. These conclusions are based on observation of the unconformable relations of the Pennsylvanian to older rocks and by the topography and structure of local mountain uplifts that are buried by Pennsylvanian strata. Despite the evidences of widespread erosion, we may conclude that most of the continent stood very little above sea level and that, excepting certain border areas, the land was generally a featureless plain. This picture of conditions is supported by studies of the character and distribution of the Early Pennsylvanian deposits.

Morrow Epoch.—During the earliest part of Pennsylvanian time the sea is known to have occupied the central and southern parts of the Mid-Continent region, but it did not extend far to the north or east. Prominence of limestone shows that the sea was mostly clear and adjacent lands too low (and probably vegetation-covered) to supply very much sand, silt, or even clay. In Oklahoma, however, and in the upper part of the Texas section there is much dark shale that marks a gradual change in conditions.

The Appalachian region was the site of continental sedimentation consisting chiefly of stream-borne materials that were carried westward from the borderland Appalachia. Broad alluvial fans were built. Extensive coal swamps made appearance, especially in the middle and southern Appalachian area. A few thin marine deposits, which are more prominent northwestward, indicate temporary eastward advances of the Mid-Continent sea on the Appalachian land area.

The Morrow epoch was brought to a close by a recession of the sea that uncovered much of the previous area of marine sedimentation. In southern Oklahoma and possibly in Kansas there were crustal movements involving folding and faulting of older rocks.

Des Moines Epoch.—The beginning of Des Moines time is marked by resumption of sedimentation, in part marine and in part nonmarine. The most important change in the conditions from the preceding epoch, especially in the Mid-Continent region, is the presence of uplands that are responsible for prominence of coarse sandy sediments and locally of conglomerates. Sedimentation was more rapid in the Ouachita and Appalachian geosynclinal areas than in other places and eventually the accumulated thicknesses of sandstone and shale amounted to several thousands of feet. Coal swamps became extensive. They were buried under silt and sand and new swamps were formed, in some places, many times. The recurrence of a certain sequence of beds, as very clearly

seen in Illinois and other states, points to a peculiar and apparently a regular oscillation of sea and land conditions that is a striking feature of Pennsylvanian history in this part of North America.

In the latter part of the Des Moines epoch the sea was alternately very extensive, as marked by presence of marine shale and limestone throughout most of the Mid-Continent and as far east as Pennsylvania, and then restricted, as shown by continental sediments laid conformably on the marine beds over large areas. The sea covered most of western North America, as shown by the very extensive occurrence of marine deposits of Des Moines age in the western states.

The Des Moines epoch was brought to a close by a general but temporary emergence of the land, which was accompanied by some erosion, but

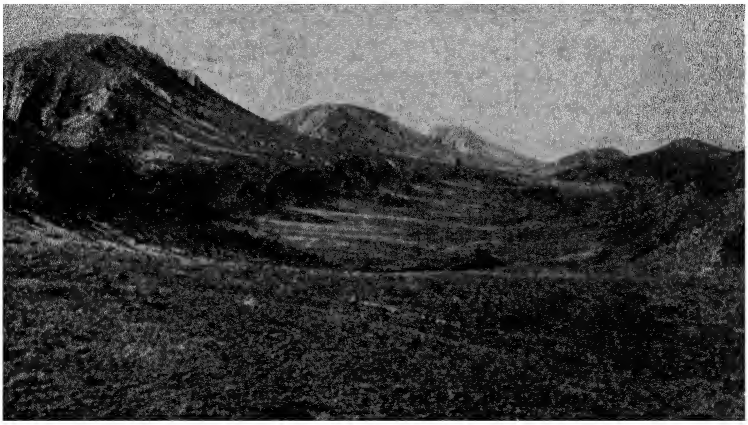


FIG. 172.—Hogback ridge of Pennsylvanian rocks and adjacent valley carved in over lying weak red beds, on eastern slope of the Laramie Mountains, southeastern Wyoming (*N. H. Darton, U. S. Geol. Survey.*)

as far as known without mountain-building. There was sufficient lapse of time or change of environment to cause distinct modification of the marine faunas.

Missouri Epoch.—The Missouri epoch was a time of wide marine transgression and of relative prominence of limestone deposition. In most places the sea was very shallow and at intervals continental sedimentation, which persisted in the east, was temporarily extended over the area of marine occupation. Calcareous deposits of Missouri age are especially found in the northern Mid-Continent and in north central and western Texas. Thin but very extensive limestones and marine shales in the northern Appalachian region show that the seas of the Missouri epoch spread temporarily eastward to the shores of Appalachia. Fossil-bearing marine beds are widespread in the western states.

The Missouri epoch was brought to a close by mountain-building in the southern Oklahoma and probably the Appalachian region and by a

general interruption of sedimentation, accompanied in places by erosion. The main folding of the Arbuckle Mountains region in southern Oklahoma occurred at this time. The Pennsylvanian and older Paleozoic rocks were uplifted many thousands of feet and in places were broken by great faults. Erosion of the elevated rock masses produced coarse conglomerates which were spread northward and southward from the mountain area. The folded rocks were eventually truncated so that in places where later Pennsylvanian deposits extended over the erosion surface, there is a profound angular unconformity. It is possible that the intense

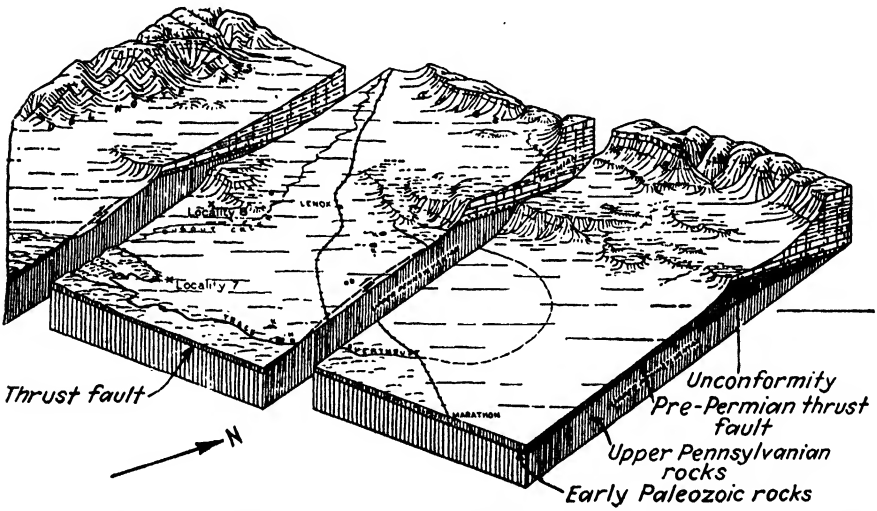


FIG. 173.—Block diagram of part of the Glass Mountains, showing Permian resting directly on Early Paleozoic rocks that are overthrust on Upper Pennsylvanian strata. The great deformation of the pre-Permian rocks occurred in Late Pennsylvanian time. (*P. B. King, Texas Bur. Economic Geol.*)

folding and faulting that affected the west Texas geosyncline in post-Gaptank time should be correlated with the disturbance that brought the Missouri epoch to a close, but this is not established. The Ancestral Rockies appear to have been uplifted at this time, for the later Pennsylvanian deposits of the Colorado region contain much coarse sand and red beds, and locally conglomerate.

Virgil Epoch.—The latter part of the Pennsylvanian period is marked by a strikingly rhythmic alternation of marine and nonmarine deposition in the Mid-Continent region and by formation of very large coal swamps in the northern Appalachians. The sea was mostly excluded from the Appalachian region. Although limestones are important in the Monongahela beds, these are all of fresh-water origin. The southern Oklahoma and Colorado mountains were eroded, the resulting sediments being laid down in adjacent territory. Near the mountain uplifts there are conglomerates and coarse sands, but farther away finer sediments

prevail. Land deposits near the mountain areas are colored red on account of thorough oxidation of iron-bearing minerals.

Close of the Period.—The general conditions that distinguished the late part of Pennsylvanian time continued with little or no change into what is classed as Permian time. The lands in the east appear to have been slightly elevated, bringing an end to prevalent coal-forming conditions in the Appalachian area, and the sea in the central and southwestern states was somewhat restricted, but, with possible exception of the west Texas region, the record of sedimentation is entirely continuous from one period to the next.

Climate.—The luxuriant and varied vegetation of the Pennsylvanian coal swamps, which exhibits general uniformity of character over a large part of the world, has long been regarded as indicating world-wide tropical or subtropical climatic conditions in this period. Evidences regarded as supporting the idea of world-wide genial, equable, and generally humid climatic conditions have been summarized as follows: (1) the large size of Pennsylvanian insects, (2) the occurrence of coral reefs as far north as Svalbard (Spitzbergen), (3) the great development and wide distribution of large foraminifera on the sea bottom, (4) the cosmopolitan character of land floras and marine faunas, (5) many structural features of the luxuriant and abundantly preserved plants, and (6) the long duration with slight changes of both faunas and floras (Dunbar).

Analysis of these criteria (Giles) raises serious question as to their validity as indicators of climate. The size of animals is not a function of temperature. Corals live today in very cool waters as well as in the warm seas. Distribution of warm ocean currents may influence the character of marine faunas, and therefore the occurrence of organisms of tropical affinities in high latitudes is not necessarily indicative of generally warm climate. Further, both plants and animals have powers of adaptation to environment which make insecure the inferences as to climatic significance based on ancient fossils. The Pennsylvanian was a time of marked evolutional change, among both plants and animals. There is basis for the conclusion that the climate of Pennsylvanian time may have been geographically varied, that much of the land area may have been temperate or cool rather than very warm, and that both dry and humid conditions may have existed simultaneously in different places and successively in the same region. The problem of interpreting the climate of past geologic time is a complex and difficult one.

ECONOMIC PRODUCTS

The chief materials of economic importance contained in the Pennsylvanian rocks are coal, oil, gas, iron ore, stone, and materials used for Portland cement and manufacture of clay products.

Coal fields of the United States of Pennsylvanian age occupy more than 200,000 square miles. The Appalachian is the most important district, the annual production of anthracite and bituminous coals averaging about 350 million tons a year, valued at about $700,000,000. The Eastern Interior fields produce about 150 million tons of coal annually, valued at about $300,000,000, and the Mid-Continent field about 16 million tons valued at $50,000,000. The combined value of these exceeds $1,000,000,000.

Oil and gas are obtained from Pennsylvanian formations chiefly in the Mid-Continent region of Kansas, Oklahoma, and Texas. Pottsville beds yield oil and gas in Pennsylvania, Ohio, Indiana, Illinois, and Kentucky. Oil is obtained from the Pennsylvanian of Wyoming, New Mexico, and Utah.

Beds of iron ore occur in the Pennsylvanian system in Pennsylvania, eastern Ohio, and northern West Virginia. The ore consists of the carbonate or oxide of iron in the form of layers or nodules. The deposits were made in marshes, precipitation of the iron dissolved in water being effected probably through action of bacteria.

Portland cement and clay products are manufactured in large quantities from Pennsylvanian rocks. Many of the clay deposits beneath the coal beds have plastic and fire-resisting properties that make them excellent for pottery and other clay products.

SUMMARY

The Pennsylvanian system is the chief coal-bearing division of the geologic column. It contains also great quantities of oil, gas, and other materials useful to man.

A well-marked unconformity separates Pennsylvanian and Mississippian rocks in most places, both in North America and in other continents, but the boundary between Pennsylvanian and Permian is not clearly defined.

Continental deposits, consisting of conglomerate, sandstone, shale, coal, and limestone, are relatively prominent in the Pennsylvanian system. To a remarkable degree an alternation of nonmarine and marine formations occurs throughout an enormous territory. This points to a general stand of the continental surface close to sea level and very frequent oscillations of sea and land conditions. Many of the marine strata and some of the continental deposits, especially coal beds, are remarkably persistent horizontally. The occurrence of a definite rhythm or cycle of sedimentation is observed in the Appalachian, Eastern Interior, and Mid-Continent regions.

Pennsylvanian rocks are very widespread in North America. They attain a thickness locally (eastern Oklahoma and western Arkansas) of about 25,000 feet.

The *Appalachian region* contains thick continental deposits derived from the borderland Appalachia on the east. Outcrops extend from Pennsylvania to Alabama. Conglomerate and sandstone are prominent, but there are much shale, in part red, and many coal beds. Thin marine limestones occur especially toward the northwest and in the upper part of the system there is much fresh-water limestone. Four "series,"

divided by arbitrarily selected coal beds, are recognized: in upward order, (1) Pottsville, (2) Allegheny, (3) Conemaugh, and (4) Monongahela.

The *New England-eastern Canada region,* extending from Rhode Island to Newfoundland, is distinguished by dominance of continental sedimentation and complexity of structure due to post-Pennsylvanian diastrophism. The beds are considerably metamorphosed in some places. Igneous intrusions have greatly affected the rocks locally.

The *Michigan Basin* contains about 700 feet of Pennsylvanian rocks, mostly of Pottsville age.

The *Eastern Interior region,* including most of Illinois, western Indiana, and western Kentucky, shows characters intermediate between the dominantly nonmarine Appalachian district and the dominantly marine Mid-Continent and western areas. Cycles of sedimentation with alternating nonmarine and marine beds are well developed.

The *Mid-Continent region* offers an exceptionally important record of Pennsylvanian history, because highly fossiliferous marine and nonmarine deposits representing almost the entire period occur adjacent to areas of recurrent mountain uplifts that show times of crustal disturbance. On the basis of interruptions in sedimentation that are correlated with these crustal movements and that correspond to major changes in faunal characters, four series are recognized: in upward order, (1) Morrow, (2) Des Moines, (3) Missouri, and (4) Virgil. The area of outcrop extends from northern Iowa to Texas.

Western North America contains widespread and locally thick Pennsylvanian deposits, the lower part mainly marine, and the upper part consisting of sandstones and red beds that are largely nonmarine. Along the Pacific Border the structure of the rocks is very complex.

Coal is a subject of special interest in connection with study of Pennsylvanian history. Chemical and physical investigations show that coal is made up of plant hydrocarbons and of a variable inorganic mineral content. Geologic evidence indicates that most coal beds were formed by accumulation of plant matter in a swampy environment, with subsequent progressive loss of volatile matter. Metamorphic changes may alter peat to bituminous coal to anthracite, and finally to graphite.

CHAPTER XIX

FORMATIONS AND PHYSICAL HISTORY OF PERMIAN TIME

The last part of Paleozoic time is called the Permian period. It is especially significant and interesting because it marks the close of one of the major divisions of earth history and presents a transition leading to the new world of Mesozoic time. The Permian witnessed profound readjustments both in the physical and in the organic realm. The continents were uplifted and enlarged, and gradually the shallow seas that had covered large portions of the lands were withdrawn. Extensive saline basins were formed in certain places and in them the world's greatest salt deposits were made. Mountain ranges were elevated in many parts of the globe. Changes in climate were widespread and important, the outstanding feature being the glaciation that affected an enormous territory in the Southern Hemisphere. On land and somewhat more slowly in the sea there were far-reaching alterations of plant and animal life that represent accelerated evolution in response to the unusual modifications of the physical world. In these ways the close of the Paleozoic era is evidenced and the preparation for a new order is signalized.

The name Permian is derived from the province of Perm in northeastern Russia, where in 1841 the British geologist Murchison discovered a series of marine, brackish, and fresh-water strata above the Carboniferous and, as shown by rather sparse faunas, beneath the early Mesozoic Triassic deposits. Rocks of Permian age occur in other parts of Europe but the system was defined in Russia because the succession of beds is more nearly complete in this region than elsewhere. Murchison's original Permian is now commonly accepted as Upper Permian and an underlying series of fossiliferous marine strata that was regarded as transitional between the Carboniferous and Permian (and therefore termed "Permo-Carboniferous") is now classed as Lower Permian. In places the Permian lies unconformably on folded and eroded Carboniferous and older rocks, but in most of Russia the Upper Carboniferous and Permian are conformable. The boundary between the two systems in the latter case is drawn at the horizon where certain fossils that are characteristic of the Permian formations first make their appearance. To some extent, therefore, the separation of the Permian from the Upper Carboniferous is arbitrary, and there are geologists who think that, in spite of the great difference in the general conditions that distinguish

these periods, they should be included together. The recognition of Permian as a distinct period seems justified, however, even though in places there is no break in sedimentation to define clearly its beginning.

It is perhaps logical to begin study of the Permian with a somewhat detailed consideration of the type section in Europe. We are chiefly concerned, however, with the geologic history shown on the North American continent, and, therefore, with the mere statement that definition of the Permian system in various parts of the world is based on characters of the European succession, we shall take up consideration of the American Permian first.

PERMIAN FORMATIONS OF NORTH AMERICA

Distribution and General Character

Rocks of Permian age occur in North America chiefly in (1) the northern Appalachian area, (2) the Mid-Continent region, including territory in western Texas and eastern New Mexico, and (3) widely scattered areas in the western part of the continent. Much the largest area of surface outcrops is in the Mid-Continent, where also are the thickest and most complete sections of beds belonging to the Permian system. The original extent of Permian deposits in eastern North America was undoubtedly very much greater than the area of present exposures, but definite evidence of this former distribution is lacking. The Permian appears to have covered much of Alaska and considerable adjacent country in northwestern Canada.

The character of the Permian rocks differs greatly in the widely separated areas that have been indicated, and it also shows much variation in some districts that adjoin. Viewed broadly, there are three main types of sedimentation: (1) normal marine deposits consisting of limestone, shale, and sandstone, many of the beds containing an abundance of fossil shells; (2) saline basin deposits consisting of chemically precipitated calcareous and magnesian carbonates, anhydrite, gypsum, and salt, accompanied by gray and red silty and clayey deposits, all very poor or lacking in fossils; and (3) continental deposits consisting chiefly of red beds of very fine to coarse texture, containing in places the bones of land animals and the generally rather poorly preserved remains of land plants. Locally, the nonmarine Permian beds contain some thin coal deposits.

Variation laterally or vertically from one of these types of deposition to another is observed in many places. For example, the lower part of the Permian section in the northern Mid-Continent is of the normal marine type but above these beds there are saline basin deposits and still higher there are thick nonmarine red beds. This shows a changing environment in this region during Permian time. A change laterally is

observed here also, for the normal marine Lower Permian strata of Kansas grade southward into nonmarine red beds of equivalent age in Oklahoma. The southwestern Mid-Continent region shows the most complex lateral variations, however, for there are contemporaneous deposits of almost every sort and the distribution of these different types shifted constantly. Accordingly, it is found that a section consisting of several hundred feet of limestone and dolomite is equivalent to one

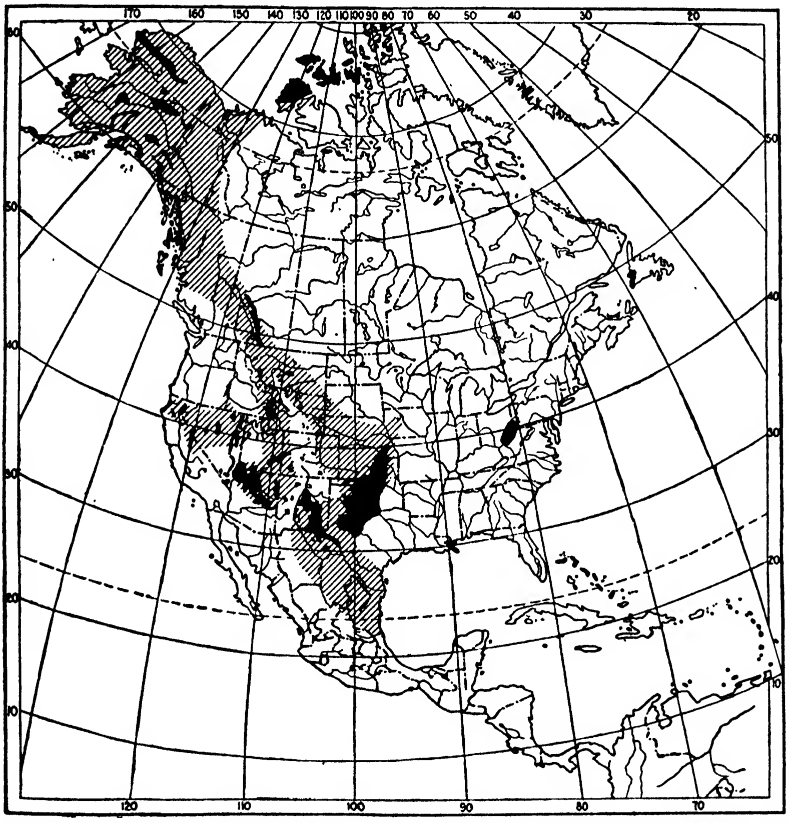


FIG. 174.—Map of North America showing outcrop area of the Permian system (black) and the inferred area of original distribution of Permian deposits (oblique shading). (*V. R. D. Kirkham, in Chamberlin and Salisbury's Historical Geology, Henry Holt & Company.*)

composed entirely of salt, gypsum, and anhydrite, and to another made up mainly of red beds, even though these respective sections are only a few miles apart.

Appalachian Region

Permian deposits are found in the northern Appalachian region (1) in the plateau country drained by the upper Ohio River in West Virginia, Pennsylvania, and Ohio, and (2) in eastern Canada and New England.

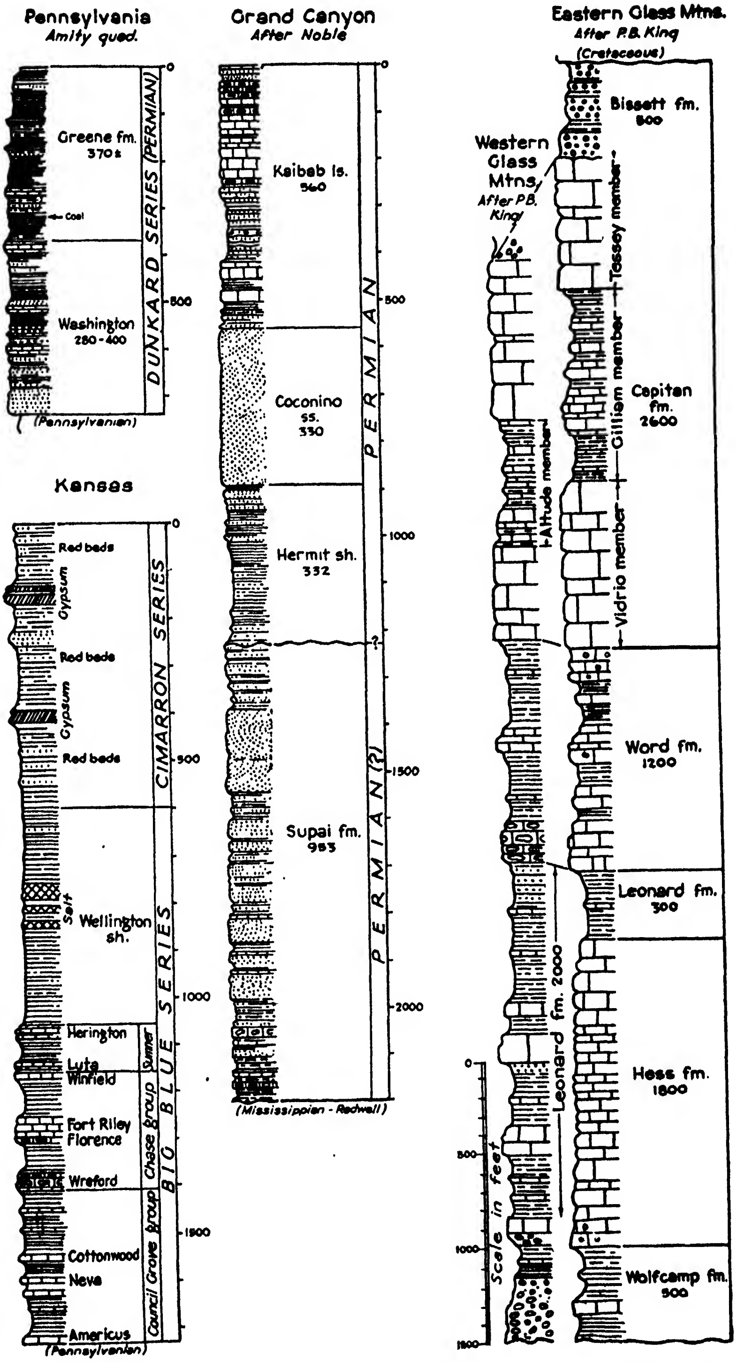


FIG. 175.—Generalized sections of the Permian system in Pennsylvania, Kansas, the Grand Canyon region, and west Texas.

West Virginia, Pennsylvania, and Ohio.—A roughly elliptical outcrop area of Permian beds, some 8,000 square miles in extent, occurs in northwestern West Virginia and adjacent parts of Pennsylvania and Ohio. The beds are practically flat-lying, and, because the topography of the region is rugged, the boundary of the Permian area is very irregular. The strata, which are known as the Dunkard series, consist of sandstones, sandy shales, a few thin limestones, and some coal beds. The color of the deposits is mainly reddish. Leaves of land plants are abundant in some beds, and it is primarily on the basis of these that the series is correlated with the Lower Permian of the European section. The presence of brachiopod shells and shark remains in certain strata, also, proves that this region was at least temporarily covered by the sea.

The maximum thickness of the Permian in this area is about 1,200 feet, but there is no way to tell how great an additional thickness of beds has been removed by post-Permian erosion. This erosion has undoubtedly carried away entirely a very large amount of Permian beds that were once present and it has reduced by an unknown amount the original area of distribution of these deposits. It is probable, indeed, that Permian formations were once continuous from West Virginia to Kansas. The Dunkard rests conformably on the top division of the Appalachian section of Pennsylvanian rocks and is really a continuation of these deposits without interruption or essential change of conditions. The only reason for classifying the beds as Permian is the character of the fossils that have been found in them.

Eastern Canada and New England.—Red and gray sandstones, sandy shales, and coarse conglomerates having a reported thickness up to 9,300 feet represent the Permian in New Brunswick, Nova Scotia, and Prince Edward Island. In places the beds dip steeply and are broken by large faults.

Near Boston is a deposit of conglomerate up to 600 feet thick containing striated and faceted pebbles. It is regarded as glacial in origin and is called the Squantum tillite, but the glacial origin of the deposit is still open to question. The deposit is probably Permian.

Mid-Continent Region

Permian strata are exposed in the Mid-Continent region in a large area extending from Nebraska to Texas and also from western Texas through much of eastern New Mexico. The outcrop belt is widest (more than 200 miles) in southern Oklahoma and northern Texas, becoming narrower to the north and south because of overlapping younger strata that spread obliquely across the Permian beds, progressively concealing more and more of them. The general inclination of the Permian in the Nebraska-north Texas belt is westward but the dip is slight, mostly 25 to 50 feet to the mile; in the west Texas-New Mexico

area the direction and amount of dip are less regular. The thickness of exposed Permian rocks is only a few hundred feet in northern Kansas but it is 7,000 feet in part of west Texas. Both continental and marine deposits are prominent, the latter including large areas and thicknesses of normal-type beds and also of the chemical precipitates of more or less highly concentrated saline basins.

The Permian formations of the Mid-Continent region can be described conveniently according to four geographic subdivisions which we shall consider briefly, proceeding from northeast to southwest.

Northern Mid-Continent.—The Permian of southern Nebraska, Kansas, and northern Oklahoma begins with normal marine sediments consisting of thin, fossiliferous light-colored limestone beds alternating

FIG. 176.—Outcrop of Permian limestone (Cottonwood) in central Kansas. (*R. C. Moore, Kansas Geol. Survey.*)

with shale. Except for slight differences in lithology and fossils, these strata are practically identical in character with the underlying Upper Pennsylvanian formations, and, like the latter, the Permian beds are strikingly persistent and uniform horizontally. There is no evidence of interruption of sedimentation between the systems and consequently there has been some uncertainty as to designation of the exact boundary. This is now determined on the basis of fossils and to some extent also on lithology.

The marine Lower Permian (called Big Blue group) has a thickness of about 1,100 feet. In the north there are workable beds of gypsum in the lower part of the group, showing that parts of the sea were sufficiently inclosed in this region to permit concentration of the sea water by evaporation to the point at which precipitation of calcium sulphate takes place. The upper part of the Lower Permian contains extensive beds of rock salt which prove that the sea in the northern Mid-Continent was at this time a highly concentrated saline water body. The salt occurs in very even layers alternating with gray or reddish clay. The thickness of individual salt beds ranges from less than an inch to 50 feet

or more, and the total thickness of rock salt exceeds 400 feet in part of the basin. The salt area covers about 20,000 square miles in southwestern Kansas, western Oklahoma, and northern Texas. It is reasonably certain that this salt sea was not a completely inclosed inland sea but, rather, that there was at least a periodic connection with open seas to the south. Reasons for this conclusion are the observations that (1) the quantity of rock salt in the basin is much too great unless there was a continued addition of sea water from outside, and (2) deposits of potash salts, which are more soluble than common salt and require a higher degree of salinity for their precipitation, are entirely lacking in this region. If a single large salt-water body had been evaporated to

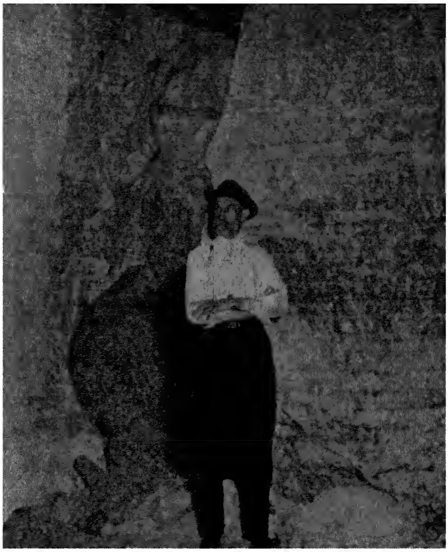


FIG. 177.—Salt in a mine near Lyons, Kans. Note the horizontal banding which is due to small inclusions of anhydrite with the salt. (*Kansas Geol. Survey.*)

dryness, deposition of potash salts should have taken place in the later stages of desiccation. The absence of potash deposits in the northern Mid-Continent apparently means, therefore, that the dwindling Permian salt sea of the north was drained southward into the Texas basin before extinction of the sea by evaporation took place.

Overlying the salt beds but still classed as Lower Permian, there are red beds (Cimarron group) that are 1,000 feet or more in thickness. These deposits consist mainly of sand- and siltstone, rather unevenly stratified and distinguished by their prevailing red color and the general absence of fossils. They are mostly nonmarine, but at certain horizons there are extensive beds of gypsum, dolomite, and in places salt, which indicate the existence of water bodies that were either large saline lakes

or temporary embayments of the sea. Deep drilling in western Kansas and Oklahoma has shown that in places the red-beds deposits grade laterally into somewhat porous dolomite and anhydrite which are the product of deposition in a saline basin. The distribution of natural gas which occurs in enormous quantity in parts of this Permian section, and also of oil, is largely controlled by these lateral changes in the nature of the rock formations.

Central Mid-Continent.—The central portion of the Mid-Continent Permian may be defined to include most of the deposits of this age in Oklahoma, the northern Panhandle of Texas, and part of the north Texas country south of Red River. The dominant type of sedimenta-

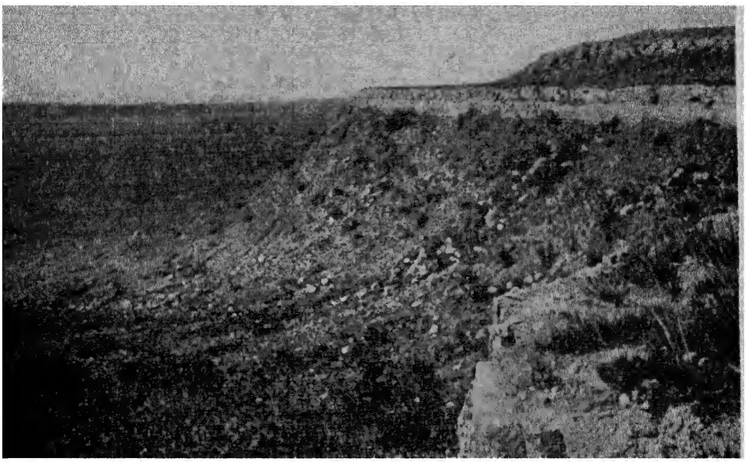


Fig. 178.—Escarpment formed by Permian gypsum beds on North Fork of Red River, southwestern Oklahoma. (*Bailey Willis, U. S. Geol. Survey.*)

tion in this region is red beds and the thickness of these deposits is locally nearly 5,000 feet. There are widespread sandstones of varying texture and thickness, some of which are coarse grits that grade into conglomerates. There is also much fine silty and clayey material, and at some horizons there are persistent beds of gypsum and dolomite. Laterally the lower red beds grade both northward and southward into nonred marine sediments, which shows that this portion of the central Mid-Continent red beds are contemporaneous with the marine formations of adjoining territory. The line of color change trends obliquely across the strike of the beds to the northwest and southwest, for the red beds reach farther north and south as one proceeds upward in the section. The distribution of the red beds and the increasing coarseness in the neighborhood of the southern Oklahoma mountains show that these uplifted areas were the source of at least part of the Permian sediments. The main sources, however, were land areas to the southeast (Llanoria)

and west (Ancestral Rockies), for the southern Oklahoma mountains were very largely buried by the red beds before the close of Permian sedimentation.

Southern Mid-Continent.—The southern Mid-Continent includes the Texas area south of Red River, where red beds largely disappear and marine formations like those in the Lower Permian of Kansas are well developed. The conditions are indeed essentially similar to those of the northern Mid-Continent district except that limestone, in part very fossiliferous, is more prominent. The beds dip westward and grade laterally in this direction into deposits of the saline basin which covers much of west Texas.

Southwestern Mid-Continent.—The Permian of westernmost Texas, beyond the Pecos River, and of eastern New Mexico is distinguished by

Open Sea	Reef	Fusulinid Beds	"Hueco" - "Gym"
Platy black limestone and siliceous shale	Massive crystalline dolomite	Thin-bedded dolomite	Gray non-dolomitic limestone.
Fossils of Guadalupian type: spinose & thin shelled brachiopods, frond-like bryozoa, cephalopods.	Massive bryozoa, corals, sponges & algae, and thick shelled brachiopods.	Profusion of fusulinids and very little else.	Echinoids; Bellerophon, Omphalotrochus and other snails, pelecypods, & sparse brachiopods.

FIG. 179.—Diagram showing different types of contemporaneous Permian deposits in the west Texas region and indicating associated faunal characters. (*P. B. King, U. S. Geol. Survey.*)

the great thickness of marine deposits in which limestone and dolomite, in part highly fossiliferous, are a very prominent part. The Glass Mountains section, about 6,000 feet thick, contains an extremely interesting succession of fossiliferous rocks, mostly limestone and dolomite, but containing also siliceous shale and chert that is composed very largely of the siliceous skeletons of radiolarian protozoans. There are unconformities between some of the formations that are marked not only by uneven, erosional contacts but by thick basal conglomerates. The constituent pebbles and cobbles of the conglomerates appear to have come mainly from uplands or mountains in the Marathon area which is south of the region of Permian outcrops. It should be recalled that an important mountain-making deformation affected the west Texas Pennsylvanian and older rocks shortly before or immediately preceding Permian time, and it is probable that the mountain area was reelevated somewhat during parts of the Permian period.

The Guadalupe Mountains area, which extends from west Texas into southeastern New Mexico, also contains a very thick succession of marine strata, the lower part consisting of dark limestone and thick sandstone, and the upper part of very massive dolomite. Some of the beds contain abundant fossils that indicate a normal marine environment.

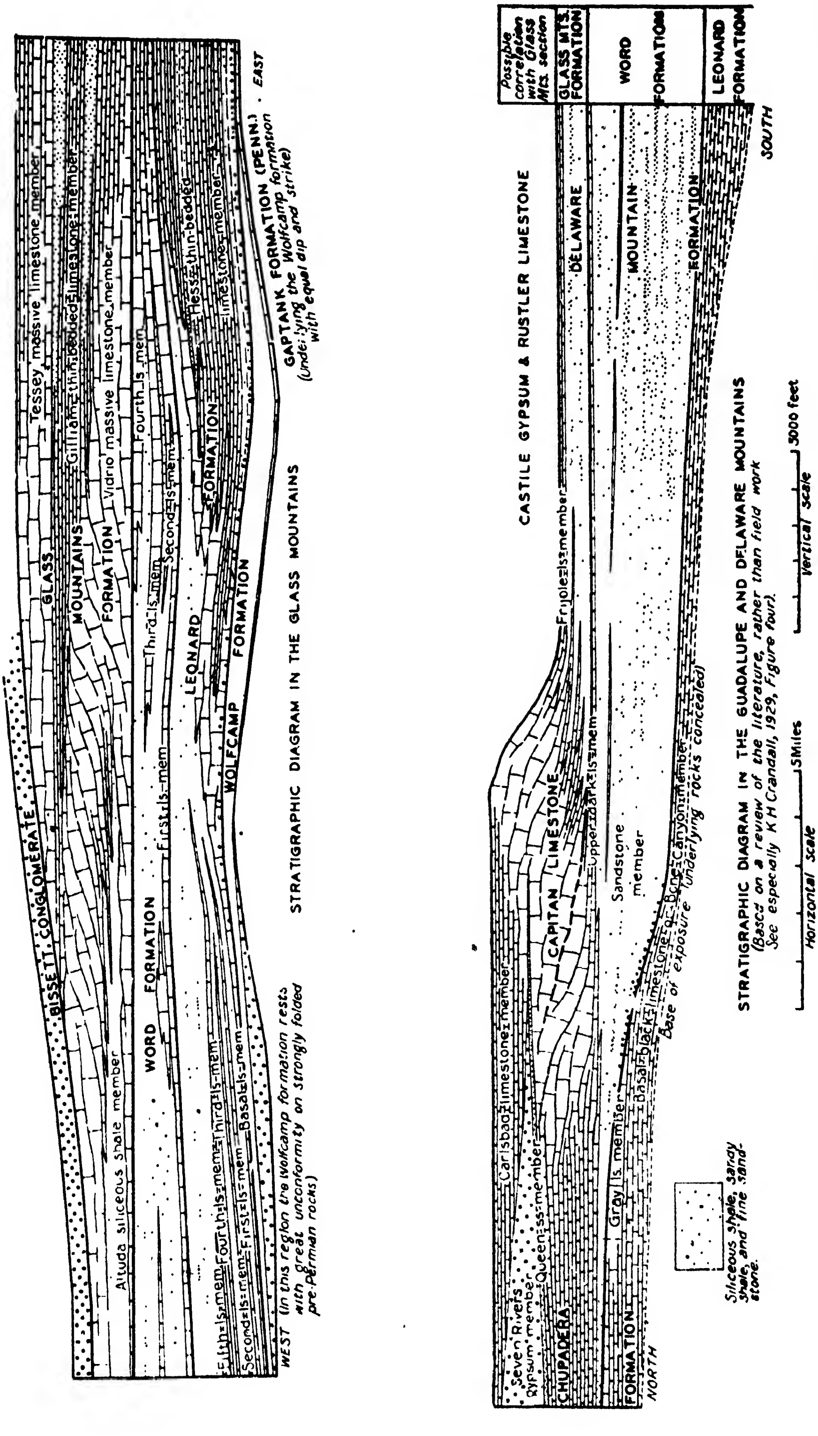


FIG. 180.—Diagrammatic east-west section of Permian formations in west Texas, showing lateral variation in types of marine sedimentation. (*P. B. King, U. S. Geol. Survey.*)

Eastward in the direction of the west Texas basin, however, there is a remarkable change in the character of the beds, for the rocks of the basin consist almost wholly of rock salt, anhydrite, or gypsum, and some dolomite. These are deposits of a highly saline water body which represents the main remnant of the formerly extensive interior Permian sea. In this basin, evaporation finally proceeded sufficiently far to produce important beds of potash salts. The lateral gradation of these saline beds into formations carrying a normal marine fauna in a westward and southerly direction is interpreted to mean that (1) the two very different types of deposits are essentially contemporaneous, and that (2) the connections of the salt basin with the open sea lay on its southwest margin. Part of the limestone and dolomite which are so thick in this

FIG. 181.—Escarpment of Permian limestones in the Glass Mountains, west Texas. (*P. B. King, U. S. Geol. Survey.*)

area may be a chemical precipitate formed by concentration of the sea water as it seeped into the salt basin. It is also possible that the thick fossil-bearing limestone and dolomite are largely of organic origin, and accordingly that they may be considered as a great "reef" or bioherm. Support for this interpretation is found in the occurrence of abundant organisms of reef-dwelling habit, such as algae, bryozoa, and cemented brachiopods.

Western North America

Permian deposits are known in most of the western states, in western Canada, and in Alaska, the most widespread and common type of sediment being red beds. In Colorado the red beds attain a thickness of at least 10,000 feet and there is evidence that much of the material was derived from local mountainous areas comprising part of the Ancestral Rockies that were formed in Late Pennsylvanian time. Farther west, in Arizona, Utah, Wyoming, and other states, there are marine limestones containing a variety of fossils, but considerable thicknesses of nonmarine red beds are present here also. An unusually well-exposed section is that seen in the upper walls of the Grand Canyon of the Colorado (see Chap. IV), where about 2,000 feet of red sandstone and shale is overlaid by 600 feet of massive limestone (Kaibab) which forms the rim of the Grand Canyon. The marine Permian of northern Utah,

Wyoming, and Idaho contains large quantities of calcium phosphate which is valuable as a fertilizer.

Recent studies of complexly folded and metamorphosed rocks in northeastern Oregon indicate the existence of several thousand feet of Permian strata in this part of the Pacific Border region. These rocks are mainly greenstones which are altered lavas containing volcanic breccia, tuff, and conglomerate. There are also metamorphosed clay shale beds (argillite) and lenses of marine limestone containing fossils. The large quantity of igneous rock points to considerable volcanic activity in Late Paleozoic time in Oregon.

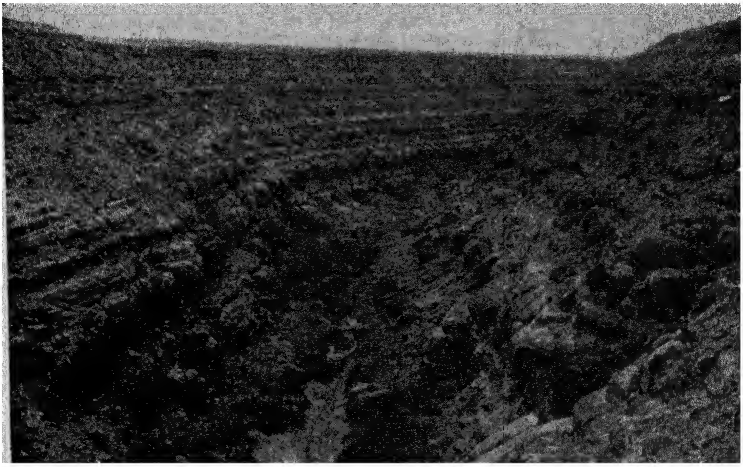


FIG. 182.—Permian limestone (Kaibab) in the Canyon Diablo, east of Flagstaff, Ariz. (*N. H. Darton, U. S. Geol. Survey.*)

PERMIAN FORMATIONS OF OTHER CONTINENTS

Europe.—The chief areas of Permian rocks in Europe are found in Russia and Germany, but there are also important exposures in the Alps region, Sicily, France, and the British Isles.

The Russian Permian, in the type region west of the Urals, begins with fossiliferous limestones of normal marine aspect (*Schwagerina* beds) and follows with beds consisting mainly of sandstone but containing also conglomerate, shale, and limestone (Artinsk and Kungur beds). All of these rocks are classed as Lower Permian. The Upper Permian (Kazan beds) consists of reddish and gray sandstones, shales, and impure limestones, and in places of beds of gypsum. There are marine fossils and also land animals and plants.

The Permian of Germany presents a well-defined twofold character, Lower Permian (Rotliegende) with dominant red beds below, and Upper Permian (Zechstein) earthy limestone, dolomite, anhydrite, gypsum, and salt above. The name Dyas, meaning twofold, has been used by many German geologists for these rocks but is now generally supplanted by the geographic term Permian. The Lower Permian consists mainly of sandstone and shale but contains also beds of conglomerate, and some salt and gypsum; in the upper part is a large amount of igneous rock in the form of lava sheets, dikes, and fragmented material. Thin beds of coal occur in many places.

Although the general nature of these beds is very unlike that of the Upper Carboniferous, there is little or no break between them. The Upper Permian contains near the base a thin copper-bearing slate that has been extensively mined. Associated with the salt, anhydrite, and gypsum of the upper part of this series are large quantities of potash salts, one of the most famous deposits being that of the Stassfurt region. The conditions of Permian sedimentation in central Europe were evidently very similar to those in the Mid-Continent region of the United States. An important feature in connection with the Permian rocks of Germany is the well-established correlation of beds containing land vertebrates and plants with fossiliferous marine strata of the Russian province, for this assists greatly in establishing the relative age of marine and nonmarine Permian formations in other parts of the world.

The Permian of England is very similar to that of Germany except that the system is much thinner. The lower New Red sandstone, which rests unconformably on Upper Carboniferous rocks, is equivalent to the Rotliegende, and the overlying Magnesian limestone, which contains some gypsum and salt beds, corresponds to the Zechstein.

Asia.—Permian strata are widespread in Asia. The most important, carefully studied sections are located in northern India (Salt Range) and the Himalaya region where marine formations with many fossils are well developed. At the base of these strata are extensive boulder beds (Talchir) that are very clearly of glacial origin. Boulders up to 6 feet in diameter, with striated and polished faces, rest in places on grooved and glacially smoothed bedrock. The thickness of the drift is reported to reach a maximum of nearly 1,000 feet. A majority of the boulders consist of rhyolite that is identifiable as having been derived from a part of peninsular India some 750 miles to the south. The direction of ice movement was thus northward away from the Equator, and this is the more remarkable since part of the existing glacial deposits are within 18 degrees of the Equator.

The Lower Permian deposits are more widely distributed, or at least better known in Asia than the Upper. The *Schwagerina* fauna of Early Permian age is present in the Himalayan region and extends far northward and eastward in China and Mongolia. The succeeding *Fusulina*-bearing limestones, which are well developed in the Salt Range of India, are Lower Permian or lower Middle Permian. Upper Permian beds containing distinctive ammonoids and fusulinids are also recognized.

Australia and East Indies.—Thick marine and nonmarine Permian deposits, including glacial beds, occur in Australia. Here also the presence of smoothed and striated bedrock, the great areal extent of the glacial materials, and their thickness prove the existence of continental glaciers. There are also iceberg-floated deposits. New South Wales, in the southeastern part of Australia, shows a thick Permian section that conformably succeeds beds of Pennsylvanian age. In order upward, the Permian includes fossiliferous marine beds 2,200 feet thick, a coal-bearing series (2,000 feet), an upper marine series (6,400 feet) containing scattered glacial boulders, and nonmarine beds with numerous important coal beds with a total thickness up to 6,200 feet.

Highly fossiliferous marine Permian beds have been found in the East Indies. The island of Timor, south of Sumatra, has furnished a succession of fossils that aids in establishing the correlation of zones in the marine Permian of the world.

Africa.—The Permian of South Africa is one of the very important occurrences of deposits of this age. It constitutes the lower part of the Karroo system, which covers 200,000 square miles and attains a maximum total thickness of about 22,000 feet. The upper Karroo beds, which are included in this thickness, are of Early Mesozoic age. The beds are chiefly of river and lake origin but at the base is a widespread, thick glacial series (Dwyka) which rests on scratched and grooved bedrock. The direction of ice movement was from north to south, away from the Equator, and the glacial beds occur within 22 degrees of the Equator. Another reason for interest in the

South African Permian deposits is the occurrence of numerous strange land animals, mostly reptiles, in some of the beds.

South America.—Glacial beds of Permian age have been found in Brazil, Bolivia, Argentine, and the Falkland Islands, showing a range in latitude from 18 to 52 South.

PHYSICAL HISTORY OF PERMIAN TIME

An outline of the significant features in the history of the Permian period, based on study of the rock formations of this age that have been described, may be arranged according to various subjects of special interest rather than chronological sequence. This is desirable both because very diverse conditions existed simultaneously in different areas and because precise correlation of the geologic record in the various Permian sections is not yet possible. We shall consider, then, (1) the general geographic conditions in North America at the beginning of Permian time, (2) the record of marine sedimentation, including the normal and saline basin types, (3) the red-beds continental deposition, (4) mountain-building, and (5) glaciation.

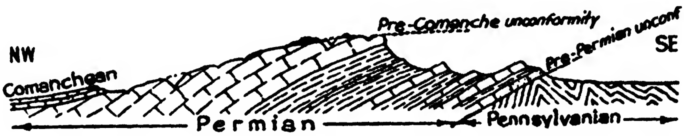


FIG. 183.—Diagrammatic section showing the structural relations of the west Texas Permian formations to associated Pennsylvanian and Lower Cretaceous formations. (*P. B. King, Texas Bur. Economic Geol.*)

Conditions at the Beginning of the Period.—The conformable sequence of Early Permian marine and nonmarine beds on uppermost Pennsylvanian formations shows that initial Permian geography was a continuation, without change, of that of the latest Pennsylvanian. There were uplands along the eastern and southeastern borders of the continent (Appalachia and Llanoria) which supplied sands, silts, and clays to the interior continental basin. The topography of this interior region was featureless and almost perfectly flat. Very gently graded alluvial plains, on which were occasional shallow lakes and coal swamps, covered a large area adjacent to the border old-lands, and in the Mid-Continent region was a broad shallow sea that joined southwestward with oceanic waters. The sea oscillated somewhat as it had done in the Pennsylvanian, alternately advancing and retreating considerable distances in the nearly flat-bottomed basin. Temporarily it even reached eastward to West Virginia in very early Permian time but it was mostly restricted to Kansas and southward.

Mountain ranges formed during Pennsylvanian time existed at the beginning of the Permian in the Appalachian region, in the Ouachita-Wichita trough extending from Arkansas to the Texas Panhandle, in southwestern Texas, and in the central New Mexico-Colorado region.

Adjacent to these mountainous areas, streams deposited gravel, sand, and finer detritus. There were evidently considerable upland and basin areas in the western part of the continent at this time, large quantities of sediment being formed by erosion and deposited by streams under conditions favoring the thorough oxidation of iron compounds which produces red colors.

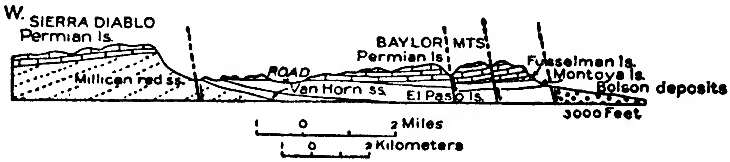


FIG. 184.—Section in west Texas showing Permian limestone resting on Silurian (Fusselman limestone), Ordovician (Montoya and El Paso limestone), Cambrian (Van Horn sandstone), and Proterozoic (Millican sandstone) rocks. (*From International Congress Guidebook* 13. *By P. B. King.*)

Marine Sedimentation.—In Early Permian time a shallow sea extended over most of the Mid-Continent region except the southern Oklahoma area. Fossiliferous thin limestones and shales accumulated to a thickness of several hundreds of feet in the submerged region. Gradually the size of the basin was reduced, especially in the north,

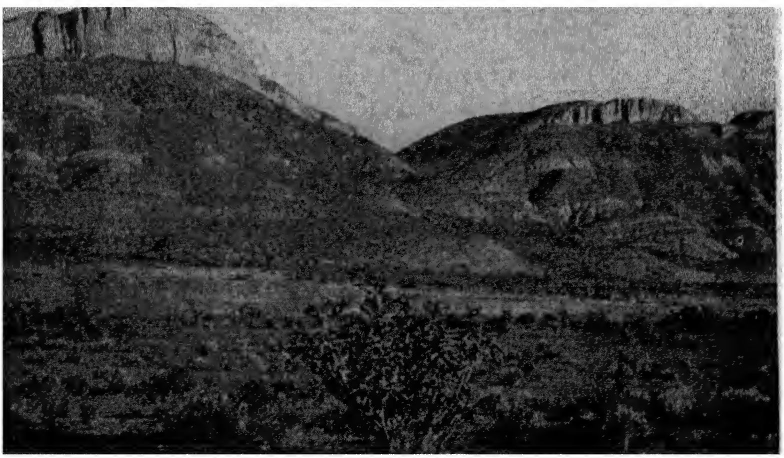


FIG. 185.—Escarpment of Permian limestone and red beds in New Mexico. Chupadera formation southeast of Engle. (*N. H. Darton, U. S. Geol. Survey.*)

and the waters became more and more concentrated, until gypsum and salt in large quantities were precipitated. Probable chief factors in the dwindling of this marine area were crustal warping and the infilling of the basin by sediments; although evaporation would be effective in increasing salinity, it would not alone cause reduction in water area so long as connection with neighboring seaways was maintained.

That the area occupied at least temporarily by Early Permian seas was very much greater than that of existing marine deposits of this age is certain. The presence of marine fossils in the northern Appalachian Permian rocks means that the Mid-Continent sea extended to this eastern area, for mountainous areas cut off the sea that lay far to the east and south. Furthermore, the Late Pennsylvanian Mid-Continent sea advanced to the Appalachian district several times, and Early Permian conditions were a continuation of those of the preceding period.

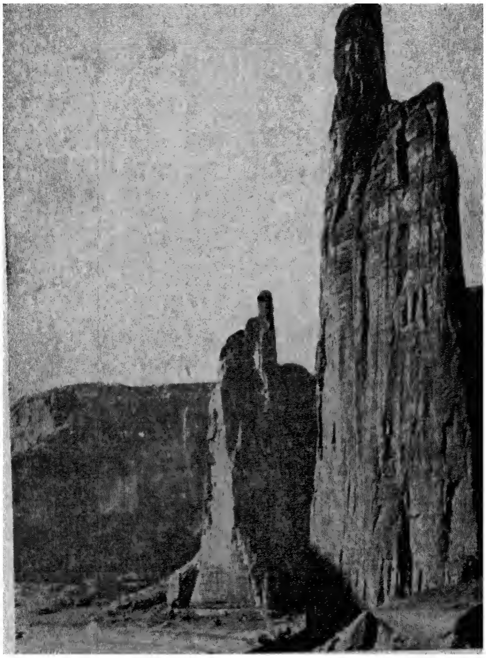


FIG. 186.—Cliffs of Permian sandstone in Monument Canyon, northeastern Arizona. (*J. K. Hillers, U. S. Geol. Survey.*)

In Early Permian time, but not at the beginning of this period, there was an extensive sea in the Western Interior region, for limestones and other rocks with numerous marine fossils are widespread here. The occurrence of greatest thickness of limestone to the southwest of the Grand Canyon region in Arizona, and the decreasing quantity of sandy and silty sediments in this direction, suggest that this part of the sea was far from land, and it is likely that connection with the Pacific lay in this direction. Post-Permian erosion has removed marine deposits that may once have been present in southwestern Arizona and southern California.

Continental Deposition.—The formation of red beds on an almost unprecedented scale is an outstanding feature of Permian history.

Deposits of this type are found in almost every Permian area and in some they compose all of the Permian section, the thickness of beds amounting to several thousand feet. Like most red beds, the Permian formations of this type are characterized by irregularity of bedding, heterogeneous lithology, and general sparsity of fossils. Poorly preserved land plants are found in places and the presence of land animals is indicated by footprints and in some localities by skeletal remains. The red beds may then be interpreted as land deposits, mostly made by streams, but in part, perhaps, laid down in shallow lakes. If this is correct, we may picture in the Permian landscape innumerable stream-built plains with gentle slopes leading from uplands toward basins in which periodic shallow lakes appeared. The climatic factors that are responsible for the prevailing red color are in dispute, for it is held by some that they denote strong aridity, by others alternate wetting and drying in a semi-arid to moderately humid climate, and it is known that red color of sediment may be produced in very moist tropical conditions. The association of red beds with salt and gypsum in the Permian formations is certainly suggestive of warm, dry climate. The evidence of plants and to some extent of animals accords with this view.

Mountain-building.—The latter part of Paleozoic time is especially characterized by mountain-building in many parts of the world and it is believed that the crust-deforming forces culminated during Permian time. Conclusive proof of the exact time of major folding and faulting of the rocks is often lacking, however. We may recall the simple, almost obvious deduction as to the geologic date of a deformative crustal movement: that the time of disturbance must have followed the making of the youngest rock strata that are involved in the deformation and must have preceded the making of the oldest subsequent strata that are not involved in the deformation. For example, the time of certain mountain-building in southern Oklahoma is rather precisely established by the observation that beds of the Pennsylvanian Missouri series are strongly folded and that beds of the next younger Virgil series, also Pennsylvanian, rest without disturbance on the upturned and eroded older rocks. The deformation thus occurred in late Missouri or early Virgil time, and it is definitely and somewhat narrowly dated within the Pennsylvanian. Let us examine the evidence concerning Permian mountain-building in North America.

The Paleozoic rocks of the Appalachian Mountain region, extending from Newfoundland to Alabama, are strongly folded. In many places there are profound thrust faults and in some districts the rocks are considerably metamorphosed. There are large masses of intrusive igneous rocks, mostly granites, that intersect Paleozoic (Pennsylvanian) and older rocks. The deformative pressure was exerted from the east or southeast, that is, from the Atlantic oceanic segment toward the

continent. The evidence of this lies in the structural attitude of the rocks which show overturning and dislocation along faults toward the northwest, and also in the fact that the degree of disturbance increases progressively toward the southeast. In the main Appalachian district south of New England, the Pennsylvanian beds are mostly, and the Permian wholly, confined to the western, less disturbed, portion of the mountain belt, although originally they may have extended much farther to the east. The fact that the Pennsylvanian is involved in strong folding, and that in New England and eastern Canada it is metamorphosed and intruded by granitic rocks, shows plainly that great compressive movements occurred subsequent to the making of these sedimentary rocks.

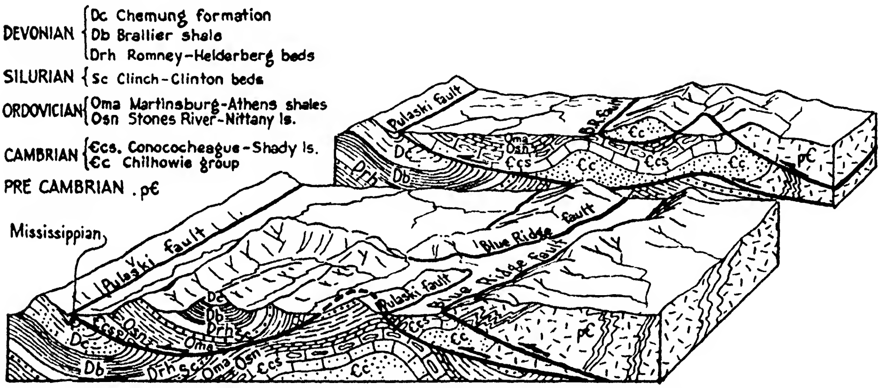


FIG. 187.—Block diagram of a portion of the Appalachian Mountains near Roanoke, southwestern Virginia, showing overthrust masses of Paleozoic and pre-Cambrian rocks. The fault planes have been deformed so that erosion has produced "windows" showing rocks beneath the fault plane surrounded by rocks of the overthrust mass. The folding and faulting are clearly post-Devonian and may be as late as Permian. (*Data from Woodward. Virginia Geol. Survey.*)

The highly deformed Pennsylvanian is largely, if not altogether, Lower Pennsylvanian, however, and it is accordingly possible that the folding occurred during Pennsylvanian time. It is now established that steep folding and large overthrust-faulting occurred in the Virginia Appalachians in Early Pennsylvanian time. Late Pennsylvanian beds are folded in central Pennsylvania but in the western part of the state both Permian and Pennsylvanian are practically horizontal. This does not mean that folding occurred after the Late Pennsylvanian and before the Permian, but merely that the remnant Permian of this region lies west of the disturbed belt. The Permian once extended much farther east, and the fact that it closely resembles the Upper Pennsylvanian and lies conformably upon it suggests that the deformation of the Upper Pennsylvanian occurred some time subsequent to the making of the Lower Permian, even though the latter is not disturbed.

Rocks identified as Permian are steeply folded and faulted in Nova Scotia, New Brunswick, and Prince Edward Island. Therefore, the

northern Appalachians at least underwent mountain-building deformation during or after Permian time. In this region and southward to Virginia, the folded and deeply eroded Paleozoic rocks are unconformably overlaid by Late Triassic formations. The time of folding is thus established as having occurred before—probably considerably before—the Late Triassic.

Summarizing, we may say that the great Appalachian mountain chain was formed by a number of Late Paleozoic deformations, some of which, possibly but not certainly including the culminating movement, occurred in Permian time. There have been normal faulting and some warping in the Appalachian region in post-Paleozoic time but no folding or thrust-faulting like that which produced the complex structure of the mountain belt has occurred since Permian times. The described conditions in the Appalachian area apply also to the mountains of south central Arkansas, southern Oklahoma, and western Texas, except that most of the major folding can here be shown to have occurred in Pennsylvanian time.

One important generalization concerning the mountain-building of Late Paleozoic time is the relation of the folded belts to geosynclinal troughs. The Appalachian geosyncline was the site of very thick sedimentation during the Paleozoic era, the total thickness of stratified formations exceeding 40,000 feet in some places. The crystalline floor of the geosyncline sagged more and more deeply as the sedimentary deposits accumulated. When great horizontal compressive forces were applied, this was a weak belt in the earth crust which accordingly yielded, the stratified rocks being folded, faulted, and locally metamorphosed. Accompanying the readjustment were igneous intrusions. It is observed that development of a geosyncline has been almost invariably followed ultimately in geologic history by elevation of the geosynclinal tract to form a mountain chain.

Mountains were formed in other continents near the close of the Paleozoic era. The so-called Paleozoic Alps of Europe, trending eastward across the central part of the continent, were mainly built in Carboniferous time, but there were movements also during the Permian. Similarly, there are important Late Paleozoic mountains in Asia, Australia, and South America.

Glaciation.—Continental glaciation on a large scale, affecting especially the Southern Hemisphere, is an outstanding event of Permian time. The distribution and general nature of the glacial deposits have been described. The great thickness of the drift in some places and the occurrence of glacial materials at several horizons, distributed through thousands of feet of continental and marine strata in some localities, indicate that the magnitude of the Permian glaciation considerably exceeds that of the last Ice Age in Pleistocene time.

The occurrence of glaciation is associated with the general elevation of the continental areas and the uplift of mountain belts in various parts of the world. It is difficult to explain, however, why the great glaciers were formed almost wholly in the Southern Hemisphere and in some cases so near the Equator, the direction of ice movement being away from the Equator in India and South Africa. Probably a main factor in the introduction of glaciation is a change of atmospheric and oceanic circulation, accompanied by temperature and precipitation changes, all

FIG. 188.—Rock surface grooved and striated by a Permian ice sheet. In the background is tillite lying upon the glaciated surface. Inman Valley, South Australia. (*R. T. Chamberlin, in Chamberlin and Salisbury's Historical Geology, Henry Holt & Company.*)

of which is dependent on the configuration and topographic character of the continental areas. It is significant that times of important glaciation are geologically associated with a strongly emergent condition of the continents and prominence of mountain-building. The causes of glaciation are discussed more at length in the chapter on the history of Quaternary time.

Gondwana and Tethys.—An interesting subject connected with the history of Permian time, and also of near-by geologic periods, is the possibly very different configuration of continental and marine areas of these times as compared with the present.

Gondwana is a hypothetical land mass of vast extent that is thought to have reached from Brazil across the Atlantic, Africa, the northern Indian Ocean, India, and Australia. Chief reasons for the assumed existence of such a great transverse continent are the observed distribution of Permian plants (*Glossopteris* or *Gangamopteris* flora) and land animals in South America, Africa, India, and Australia, and the distribu-

tion of marine fossil faunas. The occurrence of the same or very closely related species of land life in different parts of Gondwana has been considered to require a continuity of land, and such a continuous land area would serve as a barrier to intermigration of southern and northern marine life. Opposed to the existence of hypothetical Gondwana—at any rate if it is thought to have occupied a large part of the northern Indian Ocean—is the strong evidence of permanence of the continental and oceanic areas. It is possible that connection of South America, Africa, and Australia by way of Antarctica might explain peculiarities of distribution of land life in Permian time.

FIG. 189.—The Mid-Kansas Transcontinental Yates A 30 well in the Yates pool, west Texas, flowing a 10-in. stream of oil about 200 feet high.

The oil comes from Permian limestone at a depth of 1,070 feet. The well flowed 8,528 barrels an hour, indicating a potential yield of 204,680 barrels a day. (*Hennen and Metcalf, Bull. Am. Assoc. Petroleum Geologists.*)

Tethys is the name applied to the persistent seaway that in much of geologic history extended eastward from the Mediterranean across southern Asia to the Pacific. Important Permian marine deposits were made in Tethys.

ECONOMIC PRODUCTS

The chief economic products of Permian rocks are oil, gas, salt, gypsum, potash, coal, phosphate, and copper. The great *oil fields* of west Texas derive their production almost wholly from Permian beds. Huge quantities of *natural gas*, comprising the largest present known reserve of this fuel on the continent and amounting to upward of 20 trillion cubic feet, occur in Permian rocks of the Panhandle of Texas near Amarillo and in the Hugoton field of southwestern Kansas and northwestern Oklahoma. The *salt* deposits of this age occur chiefly in Kansas, Oklahoma, Texas, and New Mexico of the United States, and in central Europe. They greatly exceed those of any other geologic period, their aggregate quantity being measured in billions of tons. *Gypsum* beds of Permian age are quarried in Iowa, Kansas, Oklahoma, Texas, New Mexico, Colorado, and South Dakota. *Potash* salts have long been mined in Germany and have recently been found in commercial quantities in Texas and New Mexico. *Coal* beds occur in the Permian of all continents and are commercially important in some; they do not begin to match the coal deposits of Pennsylvanian age, however. *Calcium phosphate*, valuable as a fertilizer, is widespread in part of the western United States, including especially Utah, Wyoming, and Idaho. *Copper* occurs in a thin shale at the base of the Upper Permian of central Europe.

SUMMARY

The Permian period marks a critical, transitional time in earth history, for it brings the Paleozoic era to a close and leads to the greatly changed

conditions of the Mesozoic era. It was a time of general continental elevation and restricted seas. Mountains were formed or were in existence in all of the continents. Glaciation and in many places arid or semiarid climate are noteworthy. Physical changes induced a rapid evolution of plant and animal life that resulted in the extinction of many ancient stocks and the development of new lines that became dominant in later time. The name Permian is derived from northeastern Russia where rocks of this age are especially well developed.

North America contains extensive Permian deposits. (1) East of the Mississippi there is an area (Dunkard) in the northern Appalachians where a remnant of reddish, mostly continental, sandy beds covers parts of West Virginia, Ohio, and Pennsylvania. Other Permian areas occur in eastern Canada. (2) The Mid-Continent region contains considerable areas of normal marine Permian beds consisting mostly of limestone and shale with many fossils. These are found especially in Kansas and northern Texas. Deposits of saline basins, consisting especially of salt and gypsum and of red beds, occur above the normal marine beds. Laterally, also, these formations grade into red beds that are especially well developed in the Oklahoma region. Western Texas and eastern New Mexico contain fossiliferous marine limestone and dolomite beds several thousands of feet thick. Toward the basin that occupies much of the Texas Panhandle these beds grade into thick saline deposits consisting mainly of salt, anhydrite, gypsum, and dolomite. (3) The western part of the continent contains widespread red beds of Permian age, in places up to 10,000 feet thick, and also marine formations including thick limestone in Arizona, and phosphate-bearing strata in Utah, Wyoming, and Idaho. Complexly folded volcanic rocks occur in Oregon.

Europe contains a thick section of fossiliferous marine Permian rocks in Russia, and in Germany there is a twofold development consisting mainly of continental red beds and saline basin series that grade laterally into the marine deposits. India, Australia, South Africa, and South America contain extensive Permian deposits that include thick and widespread glacial drift.

Chief features in the history of Permian time are (1) the continuation of Late Pennsylvanian conditions with no essential change in very much of North America and some other regions; (2) the existence of a shallow sea in the Mid-Continent region in Early Permian time and the temporary extension of this sea eastward to the Appalachian area; (3) the partial inclosure and desiccation of the Mid-Continent sea, producing large saline deposits; (4) the deposition by streams and in shallow lakes of red beds over a great part of the Mid-Continent and western states; (5) invasion of a large territory in the western part of the continent by a sea from the Pacific; (6) mountain-building, chiefly in the Appalachian region in North America, affecting parts of each of the continents; and (7) glaciation on a large scale, especially in the Southern Hemisphere.

CHAPTER XX

LIFE OF LATE PALEOZOIC TIME

LATE PALEOZOIC ANIMAL LIFE—THE AGE OF FISHES AND AMPHIBIANS

General Character.—The animals that existed during the later part of Paleozoic time, considered together, are not strikingly different from those of the earlier part of this era. Naturally there were many changes, a decline of some groups and an advance of others, but practically all orders of Early Paleozoic organisms persisted. There is, accordingly, a certain unity to the character of life belonging to the era. In later Paleozoic, as in earlier times, invertebrates were strongly dominant and, although their number was not greater than in subsequent eras, the Paleozoic era is well designated the "Age of Invertebrates."

The main development of Devonian and later periods is seen in the rise of the fishes and the beginning of amphibians and reptiles. The Devonian is sometimes called the "Age of Fishes" because a variety of fishes, including many kinds of sharks, enamel-scaled fishes and lungfishes, is first known from this period. There was no decline of fishes in Mississippian and Pennsylvanian times, but, as they yielded the center of the stage to amphibians and reptiles, these latter give special character to the post-Devonian part of the Paleozoic era. The distinctive features of the different kinds of life will be reviewed briefly.

Protozoans

Protozoans are first important as an element in later Paleozoic fossil faunas in Pennsylvanian time when the "wheat-grain" shells termed fusulinids occurred in such vast numbers that they form a considerable part of many rock layers. Other kinds of protozoans are present also. It is true that shells of this class are known in Devonian and Mississippian rocks but only one species (*Endothyra baileyi*) in parts of the latter need be mentioned as very common locally. It consists of a flat spiral coil of tiny, subglobular chambers.

Fusulinids.—The fusulinid shells of Pennsylvanian and Permian time are spindle-shaped, some of them long and thin, others nearly spheroidal, and they range in length along the axis from 1⁄16 to more than 1 inch, the average being about 3⁄8 inch. They are distinguished from foraminifera that have been described previously by the shape and the much greater size of the shell and by their somewhat complex internal structure. The Early Pennsylvanian fusulinids (*Fusulina*) have mostly simple, nearly plane septa that divide each spiral turn of the shell into chambers; those of Medial and Late Pennsylvanian time (*Triticites*) are distinguished by moderately wrinkled septa, and some of those of latest Pennsylvanian and Early Permian age (*Pseudofusulina*) have highly fluted septa. In the Permian period, several highly specialized fusulinid genera appeared. There is thus a well-marked evolution of this stock during its

existence which terminated before the close of Paleozoic time, and most of the very many species are valuable index fossils. The fusulinids were bottom-dwelling foraminifera but they spread very widely over the world, being abundant not only in America but throughout most of the Old World. The foraminifera, along with other microfossils, are extensively used by paleontologists as an aid in identifying and

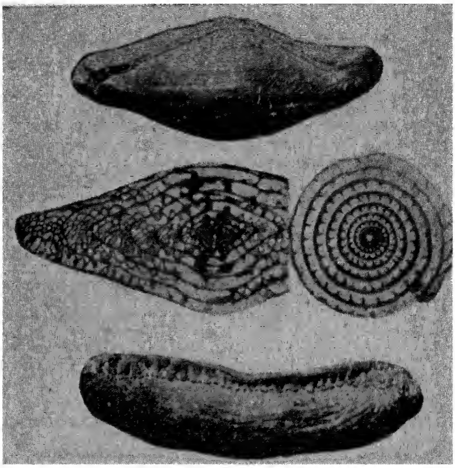


Fig. 190.—Fusulinids (*Triticites*) from Pennsylvanian rocks of Oklahoma.

The upper specimen shows the average shape which is expanded in the middle and pointed toward the ends (× 4). The bottom specimen represents a type that is common in some beds (× 4). Longitudinal and cross-sections in middle show internal structure (× 5.5).

correlating the Pennsylvanian and Permian formations penetrated by the drill in the Mid-Continent oil fields. It is interesting to find numbers of perfect, unmutilated specimens of these delicate fossils in well cuttings.

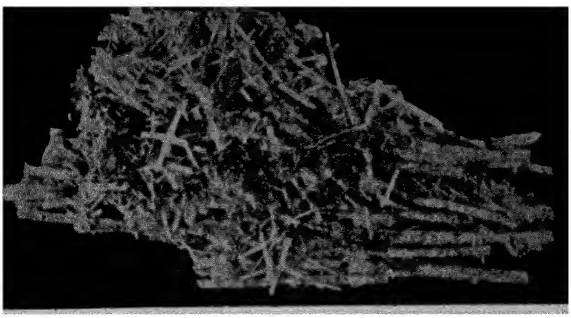


Fig. 191.—Six-rayed spicules of a Pennsylvanian siliceous sponge (*Hexactinellida*) from western Illinois (× 5). (*After J. M. Weller.*)

Sponges

Sponges of several sorts are known from each of the later Paleozoic periods. Some formations are specially characterized by abundance of sponge spicules or the presence of certain species of sponges. The massive stony types (lithistids) are much less common than the beautiful and delicate glass sponges (hexactinellids), of which a variety is found in Devonian rocks, or other kinds seen in Mississippian and younger

rocks. A glimpse of sponge life in the Upper Devonian seas of western New York is afforded in an exhibit at the State Museum at Albany (Fig. 192).

Hydrozoans

The hydrozoan class of coelenterates was represented in the Devonian and part of Early Mississippian time by graptolites and stromatoporoids, neither of which are known later.* Of the *graptolites*, all but the long-lived and stratigraphically unimportant dendroid group became extinct by the close of the Silurian. Except for the observation, well shown here and in other biologic groups, that the unspecialized graptolite stocks are in general the last to endure, this class may be ignored. *Stromatoporoids*, on the other hand, increased in numbers and variety, reaching in Devonian

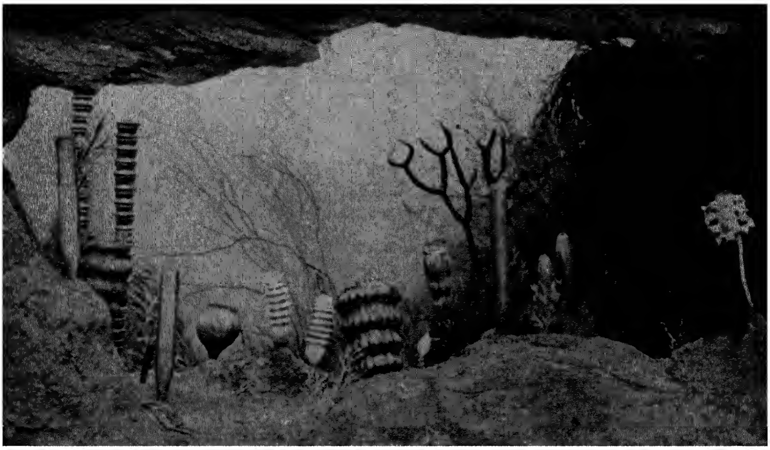


FIG. 192.—Restoration of a group of Late Devonian sponges from New York. Exhibit in the New York State Museum, Albany. (*R. Ruedemann.*)

time the peak of their career. Some colonies were truly gigantic in size, forming calcareous deposits several feet thick and as much as 10 feet across. Locally they make reefs and may be accounted important as rock builders. The stromatoporoids disappeared suddenly, for they are not found in post-Devonian beds, unless possibly certain Cretaceous fossils belong here.

Corals

Devonian Corals and Coral Reefs.—At no time in the Paleozoic were horn corals so numerous or varied as in the Devonian. They ranged in size from less than ¼ inch in length and width to more than 2 feet in length and about 4 inches in width. Some of the very common kinds (like *Cyathophyllum* and *Heliophyllum*) had numerous, evenly spaced septa without a fossular depression in the calyx; others (such as *Zaphrentis* and *Aulacophyllum*) are distinguished by the presence of well-defined fossulae. There are variously specialized forms. For example, one long-ranging genus (*Amplexus*), which is represented by several Devonian species, has extremely short septa and very numerous horizontal tabulae; another (*Cystiphyllum*), which appeared in the Silurian and died out in the Late Devonian, lacked distinct septa and had almost all of the space within the outer wall filled by a vesicular growth of dissepiments. One of the peculiar and interesting horn corals is a slipper-shaped form (*Calceola*) that is abundant in some of the European Devonian strata but is uncommon in this country.

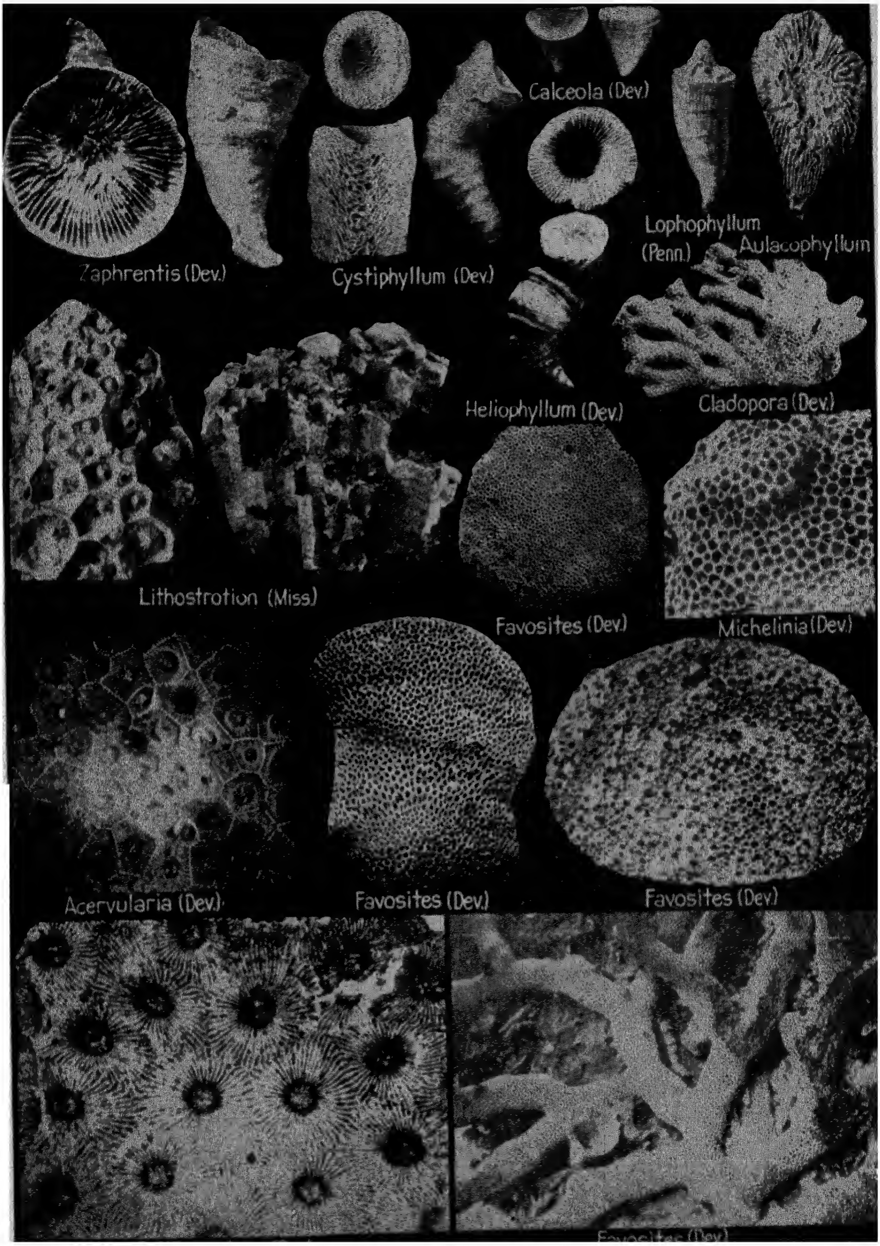


FIG. 193.—Representative types of Late Paleozoic corals (one-third natural size).

Compound corals were remarkable in their variety, beauty, and profusion. Two groups are distinguishable, one with relatively large coral individuals that have well-developed septa, and the other (*Tabulata*) with small corallites that lack distinct septa but have numerous tabulae. The first group differs from the solitary or horn corals only in the colonial mode of growth; indeed, there are some genera that include both types of growth. The individuals in many types of colonies are sufficiently separated to permit development of the normal cylindrical form of each coral (*Diphyphyllum*, *Cyathophyllum*). There are also many types in which the individuals were crowded so closely together that the cross-section of each coral became polygonal (*Acervularia*, *Phillipsastrea*). The tabulate corals include a variety of forms, among which the honeycomb coral (*Favosites*) is most common and generally known.

At many places in the shallow inland seas the corals grew in greatest profusion and were largely instrumental in building reefs. Some of these are now seen in the Devonian areas of southeastern Wisconsin, Indiana, Ohio, and Kentucky. One of these which is famous because of the beauty and variety of silicified fossil corals that have been collected from it, is located near Louisville, Ky. The coral reef which was encountered by the river in establishing its course is harder than the rocks adjacent and accordingly formed an obstruction at this point, which is known as the "Falls of the Ohio."

Mississippian Corals.—The Mississippian and later Paleozoic formations do not contain nearly so many kinds of corals nor, in general, such numbers of specimens as the Devonian, yet there are several species and some genera that are restricted to this part of the geologic column. Among horn corals, species of *Zaphrentis* were most common. The compound types were represented among others by *Michelinia*, somewhat like the honeycomb *Favosites* but coarser; the many-tubed coral *Syringopora* and the shorter-tubed, more recumbent growths of *Monilopora;* and the moderately large, cylindrical or prismoidal corallites of *Lithostrotion*, which is an important index fossil of the St. Louis limestone.

Pennsylvanian and Permian Corals.—Pennsylvanian corals are about as common as those of the Mississippian rocks but the species and most of the genera are different, horn corals being more numerous and widely distributed than the colonial kinds. The genera that may be specially mentioned are *Lophophyllum*, somewhat like *Zaphrentis* but with a prominent central axis (*columella*) that in most specimens forms a spike-like projection in the center of the calyx; *Campophyllum*, which is 1 to 2 inches across and in some cases nearly 12 inches in length and which occurs in such abundance at some zones as to make up most of the stone; and *Chaetetes*, which is distinguished by the very minute size of the closely packed tubes and by the massive growth of the colonies, which may be more than 3 feet in diameter.

The Permian is noteworthy because of the nearly complete absence of corals. The Paleozoic coral stocks were on the decline, for practically all of them disappeared before the close of the era.

Crinoids

There are four main groups or orders of crinoids, and of this number three (Inadunata, Flexibilia, Camerata) are restricted to Paleozoic time, excepting only a single genus that survived into the Triassic. The fourth order did not appear until the beginning of the Mesozoic. Some of the crinoids were extraordinarily abundant in the older Paleozoic, but the maximum development is clearly seen in the later part of the era, especially the Mississippian period.

Inadunate Crinoids.—The inadunate crinoids include the simpler and in general smaller types in which there are only two or three circlets of plates in the calyx below the arm bases. The plates are mostly smooth and unornamented. The arm structures are relatively simple in that each branch consists of a single series of small plates; some genera have lateral branchlets (*pinnules*), while others lack them.

This generalized and conservative crinoid stock is very well represented in the Devonian and Mississippian faunas but it was overshadowed by the profusion of camerate crinoids. Some of the Mississippian inadunates were larger than average and had unusually heavy, thick plates. A few genera became specialized in the loss of stem during adult life. *Edriocrinus*, of Early Devonian time, belonging in this group, had very broad, strong-looking arms and is believed by some to have used them

FIG. 194.—Crinoids on slabs of Mississippian limestone. These specimens show the calyx with attached arms and the stem by which they were fastened to the sea bottom. (*U. S. National Museum.*)

in crawling about, much like a starfish (Fig. 195). A very graceful free-swimming type with 10 feathery arms is *Agassizocrinus* of the Late Mississippian seas when inadunates became the sole surviving type of crinoids.

Abundance of crinoid stems and plates in many of the Pennsylvanian marine strata of the Continental Interior shows that the race was by no means exhausted, but the number of known species is greatly inferior to that of the Mississippian. A hundred or more complete crinoid "heads" have been collected in an hour from a locality in the Pennsylvanian rocks of eastern Kansas, and these fossils are unusually abundant in a few other places. We are reminded that the ancient crinoids, like those of today, were rather gregarious in their habits, and the conditions of local sedimentation were undoubtedly very important, also, in determining the number and the perfection of preservation of these delicate creatures. A certain calcareous shale bed (Lane) at Kansas City, Mo., has yielded many remarkably fine crinoid specimens with arms and stem attached, most of the collections being made in down-town building-site excavations. For a time in the Pennsylvanian period this was a quiet spot in the sea where crinoids settled peacefully in the soft muds for their long sleep, to awaken in the clamor of building a city.

Permian crinoids are rare. An unusually interesting assemblage of these fossils has, however, been described from Permian rocks in the East Indies (Timor).

Camerate Crinoids.—Probably the most specialized and certainly the most abundant crinoid class in later Paleozoic time was the camerate

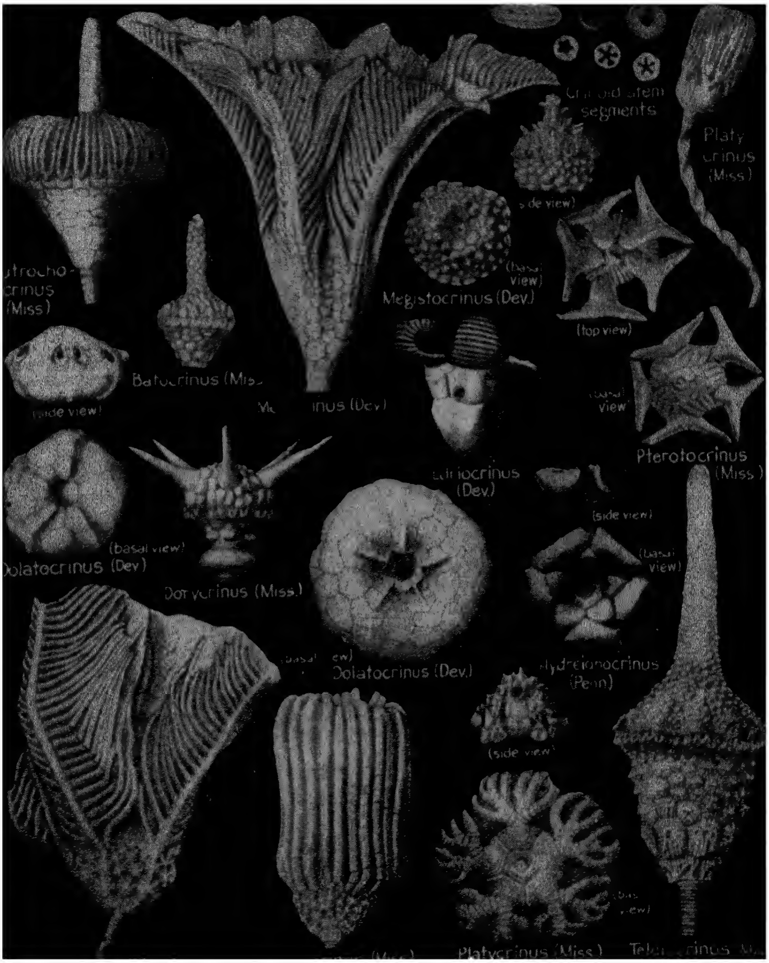


FIG. 195.—Representative types of Late Paleozoic crinoids (one-half natural size).

or "box" crinoid. This type is distinguished by the proportionately large calyx that includes a part of the arm series rigidly united with other plates.

Camerate crinoids are first known in Ordovician deposits and they are important in the Silurian. During Devonian time there was relative increase and specialization of certain lines, but in the Early Mississippian epoch an almost explosive expansion of the camerates made them the outstanding element in marine invertebrate life.

At this time the shallow seas of the central Mississippi Valley were a vast "sea-lily" garden, the remains of crinoid skeletons serving to compose the larger part of limestone strata 200 to 500 feet thick and covering tens of thousands of square miles. More than four hundred different species have been described from this region. Some had small, delicate plates and very slender, feathery arms; others had a large calyx composed of thick heavy plates and were variously ornamented with knobs and spines. A variety of specialized forms is seen. *Agaricocrinus* shows a strongly concave base and prominently elevated upper surface; *Strotocrinus* has an umbrella-like expansion of the calyx at the arm bases; *Dorycrinus* bears hornlike spines; *Pterotocrinus* is distinguished by large, solid calcareous "wing plates" on the top; and several genera have very tall, upward-reaching anal tubes. Advanced evolution is indicated in several types by reduction in the number of plates in the basal series, the normal number, five, being reduced to three or even two. The genus *Platycrinus*, which was very abundant in the Early Mississippian, had elliptical stem segments and the stem was twisted.

From the standpoint of usefulness of these fossils in identification of the stratigraphic divisions in which they occur, it is interesting to observe that most of the species and even some genera are very short-lived. Thus, most of the earliest Mississippian (Kinderhook) crinoid species disappeared before the beginning of the succeeding epoch (Valmeyer) and in the latter there are four or more zones in which less than 5 per cent of the species persist from one zone to the next. This short vertical range is characteristic of complexly organized, rapidly evolving organisms. The only difficulty in making largest use of the crinoids in correlation of beds is that the calices, which are necessary in most cases for identification of species, are commonly broken into separate plates and scattered. Except in a few localities, complete crinoid "heads" are uncommon.

Fossil Crinoid Localities.—North America furnishes some of the most famous crinoid-collecting places in the world. The best Devonian crinoids come from New York, Michigan, and along the Ohio River near Louisville, Ky. A slab of lower Devonian limestone from eastern New York in Peabody Museum, Yale University, shows more than three hundred complete crinoid calices. Most prolific of all are some Mississippian localities, especially near Burlington, Iowa, and Crawfordsville, Ind. Many remarkable slabs have been collected in central Iowa near the little town of Le Grand. Chief foreign areas are in England, Belgium, the Rhineland, and near Moscow, Russia.

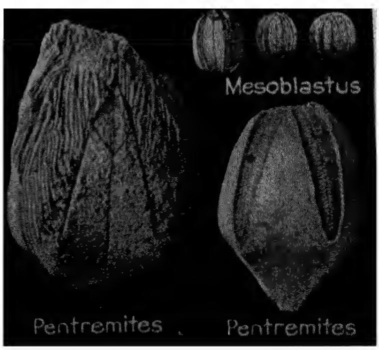


Fig. 196.—Some Mississippian blastoids (one-half natural size).

Blastoids

Blastoids are distinguished by their five-sided, beautifully symmetrical budlike form and their generally prominent, finely cross-striated food grooves (ambulacra). The average size of the calyx is small. These echinoderms were unimportant in Early Paleozoic times. They advanced during the Devonian and increased remarkably in numbers and variety in the Mississippian, but after this sudden climax they virtually disappeared. A few blastoids occur in the Early Pennsylvanian rocks of

North America, and at least one species lingered on into the Permian (East Indies).

One of the commonest Devonian blastoids is *Nucleocrinus*, which has about the shape and size of a small hickory nut and is distinguished by very narrow ambulacral areas. The most important genus in the Mississippian beds is *Pentremites*, which is broad at the base, the sides sloping gently upward toward the rounded top. Its maximum development in both species and number of individuals is found in the uppermost series (Chester) of Mississippian rocks. Certain beds of this age in southeastern Missouri, southern Illinois, and western Kentucky contain almost perfect specimens of *Pentremites* that may be collected by thousands. Many of the Mississippian blastoids are excellent index fossils.

OTHER ECHINODERMS

Cystoids.—Although upward of 250 species of cystoids are known from Ordovician, and Silurian rocks, barely a dozen are reported from later Paleozoic formations. One genus is known from the Mississippian but none definitely later.

FIG. 197.—Two types of Lower Devonian cystoids (one-half natural size).

Asteroids and Ophiuroids.—Starfishes or asteroids and brittle stars or ophiuroids are interesting but relatively unimportant elements in the marine life of the Late Paleozoic seas. Several kinds have been observed and, at least locally in New York, certain starfishes were numerous.

Echinoids.—Plates and spines of sea urchins are commonly found in many formations from Devonian to Permian in age, but complete specimens of the test are generally rare. We may specially mention a group of plates and spines from the Upper Devonian of Iowa which are perhaps more highly and peculiarly specialized than in any other known echinoid. These plates overlapped one another like shingles on a roof, and the spines, shaped like inverted collar buttons with hexagonal bases, fitted together to form a secondary armor outside the real shell, as in the reef-dwelling modern urchin *Colobocentrotus*.

Some of the Mississippian, Pennsylvanian, and Lower Permian strata contain numerous elongate echinoid spines, with a variety of ornamental spinelets on many of them. These fossils may be useful in distinguishing faunal horizons. The polygonal, usually hexagonal plates commonly have a large rounded boss in the middle, marking the place of attachment of one of the large movable spines. Smaller spine bases occur on the outer borders of the plates. Occasionally a complete test is found, most frequently in some of the Mississippian formations. The St. Louis limestone is particularly known for an echinoid that, as suggested by the name *Melonechinus*, strikingly resembles in form a small canteloupe.

Holothurians, or sea cucumbers, lack a well-knit skeletal armament such as occurs in other echinoderms, but a variety of disconnected tiny plates and spines belonging to these creatures is discovered in Late Paleozoic strata.

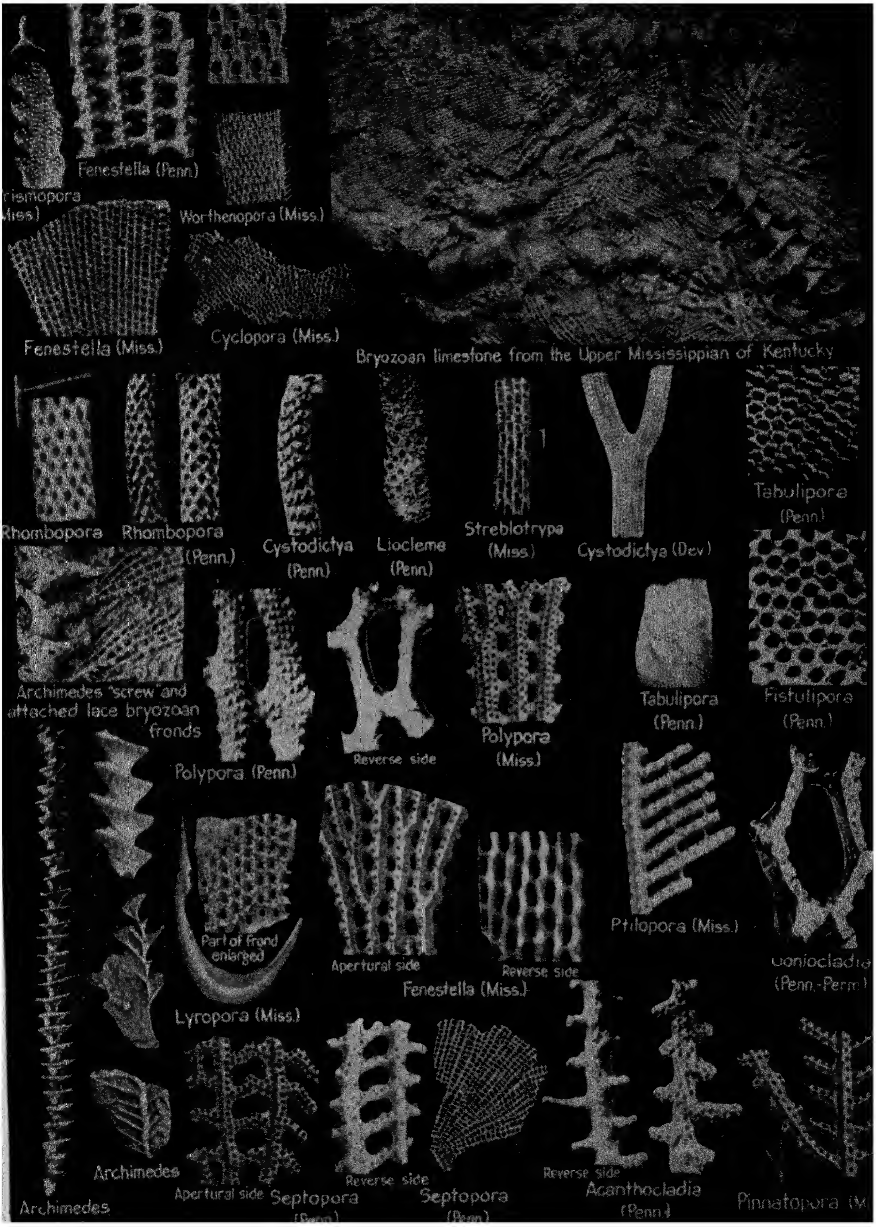


Fig. 198.—Representative types of Late Paleozoic bryozoans (mostly enlarged).

Bryozoans

The bryozoans of Devonian and Carboniferous time are characterized by the dominance of delicate lacy and slender branching types, whereas in earlier Paleozoic times the thick massive "stony" bryozoans were most abundant. The variety is exceedingly great. Though the bryozoans are less conspicuous than most other invertebrate groups, they are by no means the least interesting or valuable in correlation of the rock formations.

Slender Branching Bryozoans.—The slender branching colonies are best illustrated by *Batostomella* and *Rhombopora* which are delicate twiglike growths with apertures arranged all around the branches. In *Rhombopora* the elliptical cell apertures are somewhat depressed and are bordered by a rhombic or hexagonal rim of tiny projecting spinelets. Like many other kinds of bryozoans, these rather insignificant-looking fossils are most interesting when studied under the microscope. A common ribbon-shaped bryozoan with apertures on both sides is *Cystodictya*, and a branching form with triangular cross-section, *Prismopora*. The latter is an important index fossil in the Upper Mississippian and Lower Pennsylvanian rocks of the central United States.

Lacelike Bryozoans.—The most common lacelike types of bryozoans are *Fenestella* and *Polypora*, in both of which the tiny cells (*zooecia*) of the individual animals are arranged in rows along slender branches that are connected at regular intervals by slender crossbars. The first genus carries two rows of cells to the branch, and the second a larger number. The cell apertures all open on the same side of the colony, the opposite side being nonporiferous.

Specialized Types.—A peculiarity of some of the Mississippian bryozoans was the development of special types of solid calcareous supports. The most important one of these is seen in *Archimedes* which looks very much like a very coarsely threaded screw. This screwlike axis supported a spirally arranged lace bryozoan colony of the *Fenestella* type. *Archimedes* first appeared in the early middle part (Keokuk stage) of the Mississippian and reached greatest abundance in the latter part (Chester epoch). It became extinct shortly after the beginning of the Pennsylvanian period. Another genus that lived in Mississippian time is *Lyropora*, which had a U-shaped support like a lyre.

Brachiopods

No class of Paleozoic fossils is more important than the brachiopods. Their remarkable rise in the Ordovician and Silurian periods has been described, and at the beginning of later Paleozoic time we find them at the peak of their career. They predominate over other invertebrates in the Devonian and are not very greatly diminished in the Mississippian. The group had begun to decline, however, for numbers and variety are much reduced in the Pennsylvanian and Permian. A bare remnant of the Paleozoic brachiopod host, consisting mainly of primitive and unspecialized types, survived into Mesozoic time and persists today.

Primitive Unhinged Brachiopods.—Each of the later Paleozoic systems holds a good representation of the simple, unhinged brachiopods which have thin phosphatic shells.

The unhinged brachiopods (*Lingula*, *Orbiculoidea* and others) are much like the oldest known species that thrived on the muddy or sandy bottom of Cambrian seas.

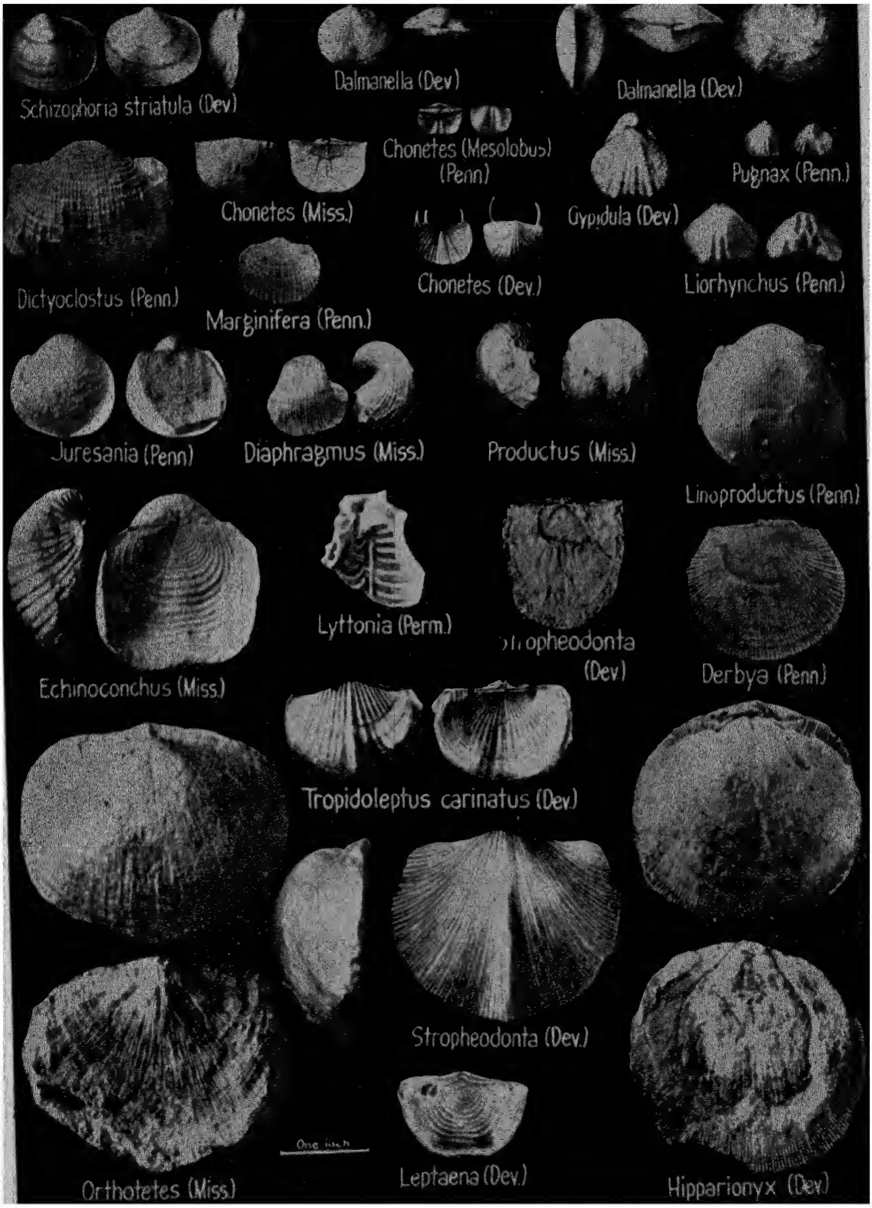


FIG. 199. -Representative types of Late Paleozoic brachiopods (one-half natural size). Productids shown include *Productus*, *Dictyoclostus*, *Marginifera*, *Juresania*, *Diaphragmus*, *Linoproductus* and *Echinoconchus*.

The fact that they occur almost exclusively in the dark shaly formations indicates that they are specially adapted to this type of environment. They are "facies fossils"

and may be expected to occur whenever the proper environment or facies of sedimentation occurs. The insignificant changes shown by these shells, despite existence of the group for scores of millions of years, means that they have little value as indicators of any given geologic horizon. They furnish good examples of an animal stock that is very stable because unspecialized, yet adapted to an environment that always exists somewhere.

Orthid Brachiopods.—Shells of the so-called orthid type (from the Ordovician genus *Orthis*), with well-developed teeth and sockets for articulation of the valves, and with other distinguishing structural features, are nearly as common in Late Paleozoic rocks as in Ordovician and Silurian strata, but the genera are partly different.

Finely striated shells of rounded outline, like *Dalmanella*, *Schizophoria*, and *Rhipidomella*, are abundant and important. The first disappeared at the end of the Devonian, the second in the Early Pennsylvanian, while the last persisted to Permian time. *Schizophoria striatula* is a common Devonian fossil, practically world-wide in distribution. An interesting Late Pennsylvanian and Permian genus, also known from five continents, is *Enteletes*. It had a globose shell with fine radial striations and broad plications interlocking in a sawtooth line at the margin.

Strophomenid Brachiopods.—The group called Strophomenacea, in which one valve is generally distinctly concave, is the most important among Late Paleozoic brachiopods, excepting only the spire-bearing shells.

There are numerous genera of Late Paleozoic strophomenids with a long straight hinge line and semicircular outline: *Stropheodonta*, *Strophonella*, *Hipparionyx* and others in the Devonian; *Schellwienella* and *Orthotetes*, which are common in the Mississippian; and *Derbya*, which is abundant in Pennsylvanian and Permian rocks.

The family Productidae is a dominant element in the Mississippian, Pennsylvanian, and Permian brachiopod faunas of the world. Walther, Schuchert, and others have applied the name *Productus* seas to the marine invasions of the continents in these periods. The forerunner of *Productus* was *Productella*, which lived in the Devonian and Early Mississippian. *Productus* itself began in the Mississippian and soon became extraordinarily abundant and widespread. The shell has a very convex pedicle valve and concave brachial valve. Surface ornamentation consists of prominent radiating ribs which may be crossed by concentric wrinkles, and there are commonly numerous long hollow spines, only the bases of which, however, usually appear on the fossils. Differentiation along various lines has led to recognition by paleontologists of numerous subgenera, of which the most important in America are *Marginifera* and *Echinoconchus*. *Productus giganteus* is the largest brachiopod known, in some cases attaining a width of 12 inches. A long-ranging member of the productid family is *Chonetes*, a small shell with a single row of hollow spines along the margin of the cardinal area of the pedicle valve. It is common in the Devonian and abundant in Mississippian and Pennsylvanian rocks of North America.

Two groups of highly specialized, peculiar-looking brachiopods that lived in the Permian may be specially mentioned. One of them (*Richtofenia*) resembles a horn coral more than a brachiopod, for it has been strangely modified by its mode of attachment and by thickening of one of the valves. It is found in Texas, eastern and southern Asia, and southern Europe. The other (*Leptodus* and allied genera) has very prominent curving ridges and grooves on the inside of the shell unlike any other brachiopod.

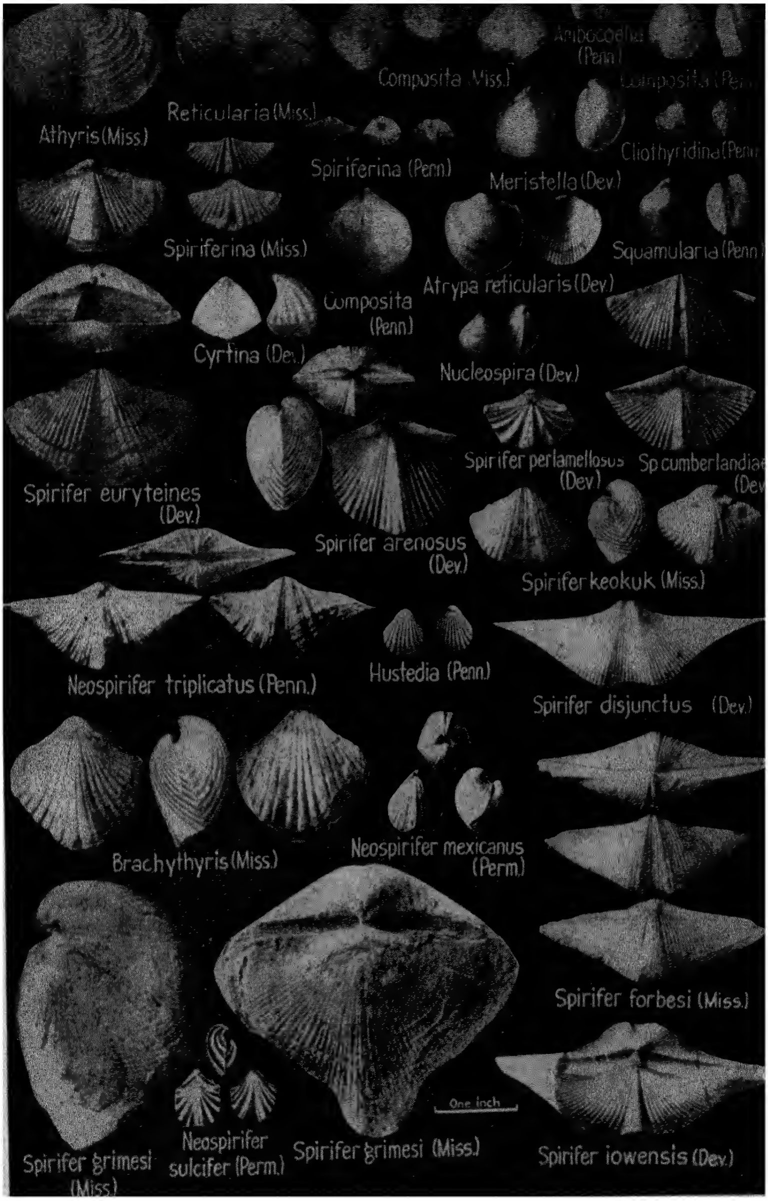


FIG. 200.—Representative types of spire-bearing Late Paleozoic brachiopods (about one-half natural size).

Brachiopods with Prominent Pointed Beaks.—The rhynchonellid brachiopods, with very short hinge line, prominent beaks, and generally strongly plicated shell, are very common in many of the later Paleozoic formations. The terebratulid group somewhat resembles the rhynchonellids in shape but the shells are smooth and they have a calcareous loop inside for support of the tentacle-bearing brachia on each side of the mouth.

There are numerous genera in these groups, especially in the Devonian but also in succeeding periods. *Rensselaeria* is one of the common index fossils of the Lower Devonian. *Stringocephalus*, a large shell that characterizes a zone in the Middle Devonian of Europe, invaded the sea of this time in northwestern Canada, coming by way of the Arctic and reaching the western United States.

Spire-bearing Brachiopods.—The spire-bearing brachiopods comprise the last and most highly developed group. This type of shell had made a small beginning in the Ordovician. It expanded considerably in the Silurian but culminated in the Devonian and Mississippian.

The most important genus is *Spirifer*, a moderate- to very wide-hinged shell with plications radiating from the beaks and generally with a well-defined median depression (*sinus*) on the pedicle valve and a corresponding elevation (*fold*) on the brachial valve. Internally, there are two spirally coiled brachial supports. In total number of known species and individuals, *Spirifer* outranks even *Productus*. The following evolutional changes may be discerned: (1) plications in early forms (Silurian and most Devonian species) simple, undivided, absent on fold and sinus; (2) plications in intermediate forms (some Upper Devonian and most Mississippian species) simple, present on fold and sinus; (3) plications in late forms (*Neospirifer*, Pennsylvanian, Permian), branching or arranged in bundles, present on fold and sinus; (4) modifications of shell structure and internal features that are made the basis of separation into distinct genera. There is a very great variety of shape and size in the *Spirifer* group, and because of progressive, rather rapid evolution many of the species are very good index fossils.

Several other genera, with differing external appearance and internal structure, are common. Among these, *Athyris*, *Meristella*, *Cyrtina*, and *Atrypa* may be mentioned. Of the last named, *Atrypa reticularis* vies with *Leptaena rhomboidalis* for the longevity record, for it existed essentially unchanged throughout Silurian and Devonian time. It is an exceedingly common shell in many places and is distributed all over the world.

Pelecypods

Pelecypods are abundant in many of the formations of later Paleozoic age, especially the shales and sandstones. The species are somewhat different in each period but the main types are very persistent and exhibit little real change. Several of the genera are smooth-shelled, rounded, subtriangular, or elongate in outline. Others have prominent concentric lines or plications radiating from the beak and a few have a combination of these ornamental features. A primitive stage of development is indicated in the majority of shells by unspecialized hinge structures

such as occur in the very youngest growth stages of many modern pelecypods.

The upper portion of the Devonian system (Hamilton, Portage, and Chemung), which in eastern North America is dominantly composed of shale and sandstone, has a large pelecypod fauna, the description and illustration of which fill two large volumes of the New York Geological Survey. The shaly and sandy beds of the Early Mississippian (Kinderhook) and the oolitic Salem limestone are the chief pelecypod zones.

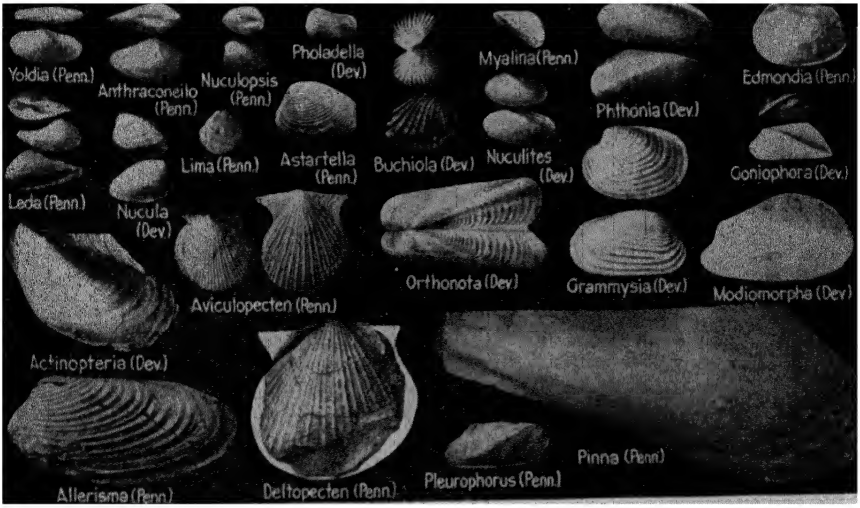


FIG. 201.—Representative types of Late Paleozoic pelecypods (about one-third natural size).

The environment which produces oolite, it may be observed, is very congenial to the mollusks as shown by many instances, including several in the Pennsylvanian. In general, the shaly beds of this period contain numerous pelecypods and gastropods, whereas most of the limestones have more brachiopods and corals. The Permian fauna appears to have a proportionately large pelecypod component.

Gastropods

The distribution and general character of the gastropods are correlated closely with those of the pelecypods. They are more abundant in the same kinds of rock and the same geologic horizons as the pelecypods, and they follow a few stable persistent patterns. One type (*Bellerophon* and allied forms) is coiled in a plane and has a large bell-like mouth. Several genera are established on different types of surface ornamentation. Shells of the *Pleurotomaria* type are characterized by a moderately elevated spire and those of the *Loxonema* type by a very tall, narrow spire. A few uncoiled or only partially coiled shells are found.

The slender little straight tubes of pteropods (*Styliolina*) and conularids (*Tentaculites*), the latter distinguished by its thicker walls and more or less regular series of rings around the shell, are exceedingly

abundant in certain Devonian beds. Both of these genera have a tubular shell that is pointed at one end and expanded evenly toward the other.

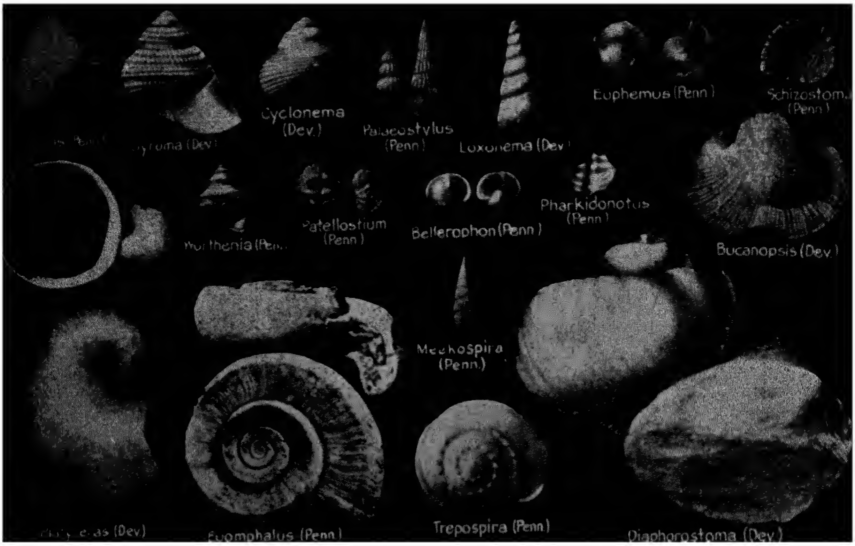


FIG. 202.—Representative types of Late Paleozoic gastropods (about one-half natural size).

Cephalopods

Two distinct groups of cephalopods are found in the later Paleozoic rocks and they occur in nearly equal numbers. The first is the type with which we have already become acquainted in the older Paleozoic rocks—the nautiloid shells. These are straight, curved, or coiled and are mainly distinguished by the simple, straight, or gently curved sutures at the edge of the septa that divide the shell into chambers. The second class, known as ammonoids, have more complex sutures and develop a higher degree of ornamentation than is observed in the first. It probably had its beginning in Late Silurian time, advanced rapidly in the Pennsylvanian and Permian periods, and achieved a remarkable culmination in the Mesozoic era.

Characters Showing Evolution.—The evolutional advancement or specialization of the cephalopods may be ascertained chiefly by observation of the following characters: (1) form of the shell, (2) surface ornamentation, (3) shape of the aperture, and (4) nature of the sutures.

In considering form of shell, it has been noted that the perfectly straight, gently tapered *Orthoceras* type is most primitive, and that the curved (*Cyrtoceras*), loosely coiled (*Gyroceras*), and tightly coiled (*Nautilus*) types represent successively more advanced modes of growth. The tightly coiled shells may be divided into groups on the basis of the shape of their cross-section or the extent to which the outer whorls are

in contact with and cover the inner. The shape of the shell may range from very flatly discoidal to extremely thick and globular, the outer border or periphery being sharply pointed, rounded, flattened, or angulated. The cross-section of a whorl similarly may vary from circular to quadrangular, polygonal, or crescentic. An abnormal shell form, seen in a few Early Paleozoic and Mesozoic families, is a spiral gastropod-like twisting or, more rarely, an erratic bending without definite plan.

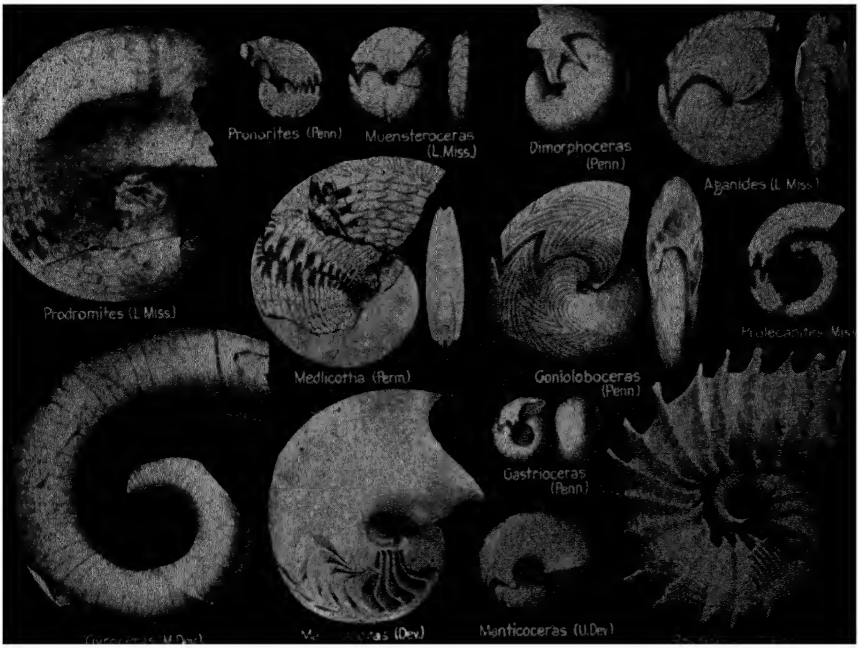


FIG. 203.—Representative types of Late Paleozoic cephalopods, the space between two of the sutures artificially darkened (about one-third natural size).

Surface ornamentation consists of various sorts of ridges, nodes, or spines, of fine lines and granulation, and of color (which in almost all cases is lost in fossilization). The majority of nautiloids are smooth, but the shells of many ammonoids are highly ornamented.

The aperture, not preserved in all fossils, is commonly simple and round but may be modified by shallow or deep indentations of the borders and by a beaklike projection of a part of the shell. The most highly modified apertures among the nautiloids are seen in Silurian and Devonian shells which have the living chamber nearly closed by inbending edges of the aperture. Some of the Jurassic and Cretaceous ammonoids have the most highly modified apertures.

The sutures are plain and smooth in the primitive nautiloids, and in modern *Nautilus* they are only gently curved. A progressive change

in the form of the sutures appears, especially among the ammonoids. From slightly curved they pass to distinctly wavy and in part angulated and then by increasing crenulation achieve a more and more complex pattern that is most extreme in some of the Mesozoic shells. The causes that led to this specialization of sutures are in doubt.

Nautiloids.—Among Late Paleozoic nautiloids we find the unprogressive, straight-shelled *Orthoceras* and various slightly ornamented allies which are almost as common as they had been in the Ordovician and Silurian. Some of the Mississippian shells

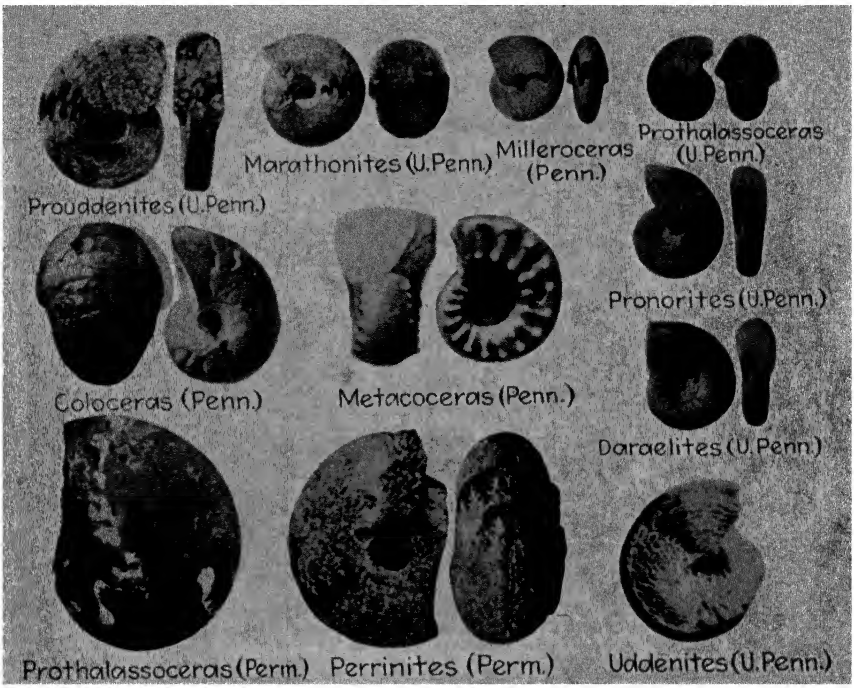


FIG. 204.—Representative types of Pennsylvanian cephalopods (about two-thirds natural size).

from northern Arkansas and southern Oklahoma have a maximum diameter of nearly 8 inches and a complete length of more than 5 feet. The fact that these straight-shelled nautiloids persisted with so little change and survived almost all of the more advanced types calls attention to an observation which holds true in many other cases: that the specialized products of evolution are in general the first to disappear, while the unspecialized conservative types live longest.

The coiled nautiloids are fairly common in each of the Late Paleozoic periods. There were several smooth-shelled species, but the ornamented types are most interesting and significant of evolutional change. An example in the Late Devonian is the frill-bearing *Rhyticeras*. Some of the Mississippian and Pennsylvanian shells had prominent nodes along the sides and a few were of large size, attaining a diameter of nearly 18 inches. One of the most common genera is *Metacoceras*.

Ammonoids.—The first ammonoids have sutures that are nearly straight, classification with the ammonoids being indicated by other characters. The ammonoid

stock is, of course, clearly a derivative of the nautiloids and features typical of the latter, such as simple sutures, a small open space left by the first-formed whorl, and the structure of the siphuncle, are found in the majority of Paleozoic ammonoids. These are sometimes grouped together under the name *goniatites*. One of the Devonian genera (*Bactrites*) has a straight shell like *Orthoceras*, and another (*Mimoceras*)

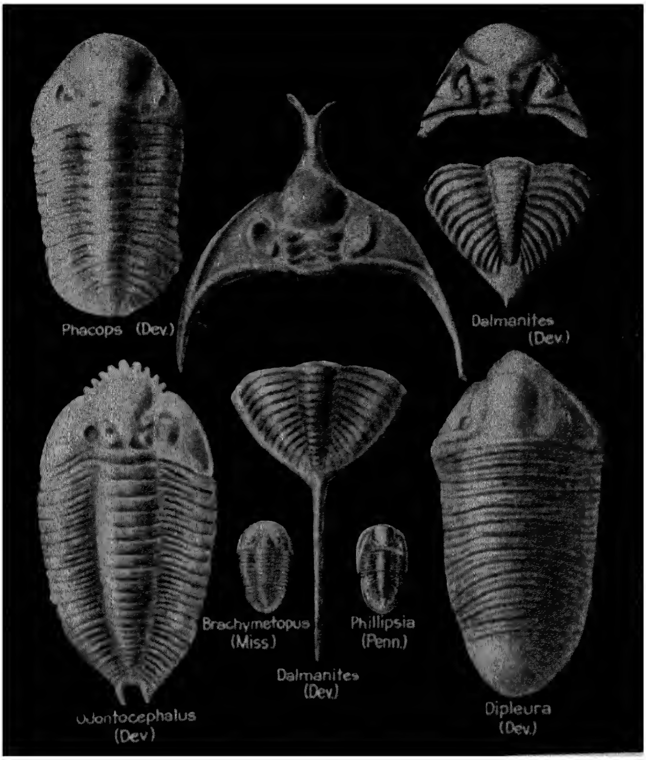


FIG. 205. - Representative types of Late Paleozoic trilobites (about one-half natural size).

has in the young shell a loosely coiled form like *Gyroceras*. The rest are tightly coiled, some with whorls barely touching, others with outer whorls partly embracing the inner, and still others so highly involute that only the outermost whorl can be seen. Several of the Devonian and Mississippian genera (*Clymenia*, *Agoniatites*, *Gephyroceras*) have moderately curved and angulated sutures. Others (*Beloceras*, *Prolecanites*) show much more numerous wavy irregularities of the sutures. Deflections of the sutures toward the aperture, termed *saddles*, tend to be rounded while those away from the aperture, termed *lobes*, are generally pointed. The sutural lobes of some Pennsylvanian genera and of many Permian shells (*Medlicottia*, *Marathonites*) show division into subordinate crenulations. Ammonoids with this type of suture, more complex than in the typical goniatite, are sometimes called *ceratites*. The culmination of ceratitic sutures occurred in the Triassic. A secondary complication of the saddles, as well as of the lobes, that developed ultimately the most complex of all sutures, distinguishes the shells called *ammonites*, but there is actually no sharp line separating these from ceratites or simpler forms. A few of the Pennsylvanian and Permian ammonoids (*Cyclolobus*, *Waagenoceras*) have ammonitic sutures. The

Late Paleozoic cephalopods of this class thus show a progressive increase of sutural complexity which foreshadows remarkable types that are so abundant in the Mesozoic rocks.

Trilobites

This distinctively Paleozoic class of animals was on the decline even in Silurian time, but it is still a noteworthy element in many of the Devonian faunas. Two groups may be differentiated. The general appearance in the one is that of a well-advanced but conservative trilobite, without frills, special ornamentation, or any unusual peculiarities, and without marks of degeneration such as appear in several of the Silurian branches. *Dalmanites* and the very abundant *Phacops* (see Figs. 90, 205) illustrate this group. The other is overdecorated and peculiarly specialized in various ways. Extreme development of spines is seen on head, body, and tail, and in one genus the central lobe of the head became very strongly bulbous. These abnormal types did not survive into the Mississippian, when only four genera of the conservative group, all belonging to a single family, are found. The number is further reduced in the Pennsylvanian, and finally there is but one, the last of the race, in the Permian. The overdevelopment in different ways and the specialization that shortly led to extinction are well illustrated by various branches of the trilobites; and the persistence of the conservative, unspecialized stock is seen in its survivals to latest Paleozoic time.

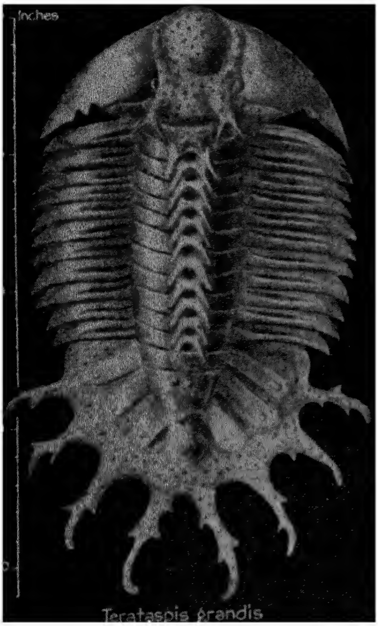


FIG. 206.—A "giant" trilobite of peculiarly specialized form from the Devonian rocks of New York.

Ostracodes and Other Crustaceans

The tiny bivalve crustaceans called *ostracodes* literally swarmed at various times and places in the shallow seas of Late Paleozoic time, if we may judge from the abundance of their shells in certain layers. The number of different kinds is also very large, some smooth and rounded, some very beautifully and delicately ornamented with granules or fine-meshed network, some with prominent bulbous nodes or ridges, and some with projecting comblike frills. In the Mid-Continent oil fields, the rock layers of Pennsylvanian and Permian age, as well as those of the

Mississippian and older systems, are commonly identified by means of ostracodes and other microscopic fossils observed in the drill samples.

Another crustacean group termed *phyllocarids*, because of the leaflike (*phyllum*, leaf) nature of their limbs, has a pair of large rounded or elongate valves enclosing the head and thoracic regions; the abdomen projects at the rear and bears three spiny processes at the end. Examples of a variety of these creatures are known from Devonian, Mississippian, and Pennsylvanian rocks.

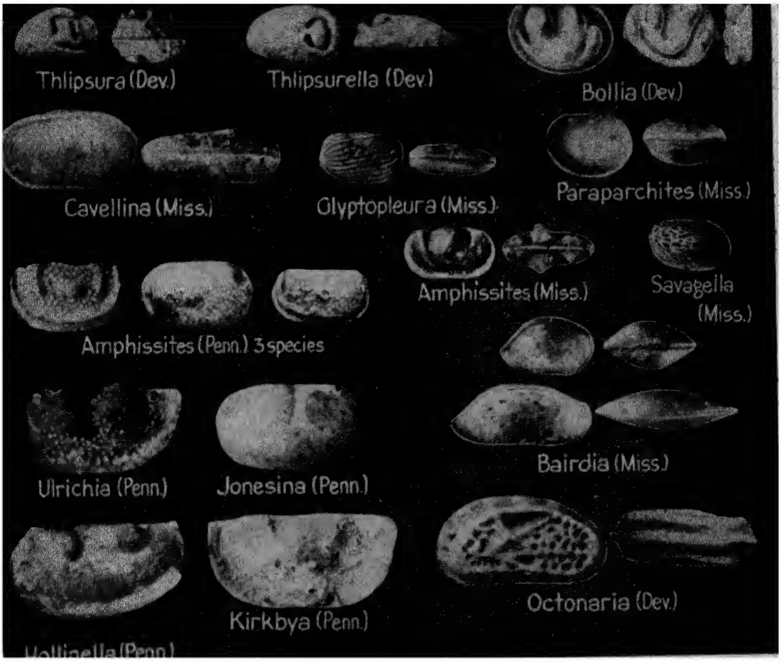


FIG. 207.—Representative types of Late Paleozoic ostracodes (much enlarged).

From the Pennsylvanian rocks in various places come several interesting fossils that are strikingly like the modern crawfishes or lobsters but are sufficiently distinct to make them assignable to a different group. A famous locality from which some of these and many other less common fossils have been collected is on Mazon Creek in Illinois, about 50 miles southwest of Chicago. The fossils, including leaves, shells, crustaceans, insects, spiders, scorpions, myriapods (thousand legs), and rarely skeletal remains of small amphibians and reptiles, occur in nodular concretions embedded in shale.

The *merostomes* include the king crabs, eurypterids, and various related forms. The eurypterids were well developed in the Early Paleozoic, especially the Silurian, when some of them attained a length of more than 6 feet. Various genera are found also in the Devonian and Carboniferous, but their association with other fossils indicates a change in habitat from an original marine environment to the brackish waters of lagoons and estuaries, and the fresh waters on land. One of the eurypterids (*Stylonurus*) in the Late Devonian had a length of more than 6 feet. Eight of its ten jointed appendages, projecting from the under side of the head, were unusually long. The Pennsylvanian and Permian formations yield several interesting relatives of the

spike-tailed king crab (*Limulus*) which indeed look very much like the modern specimens except that the fossil forms are small.

Insects

One of the developments of the later Paleozoic life that attracts special attention is the first appearance of insects. This group has expanded in later earth history until at present there are more species of insects than of all other kinds of animals put together. It is said that the only serious competitors of man are the insects. It is perhaps fortunate that the size of modern insects is not that of certain individuals of Pennsylvanian time when 4-inch cockroaches scurried over the ground and dragon flies with a 30-inch wing spread droned through the air.

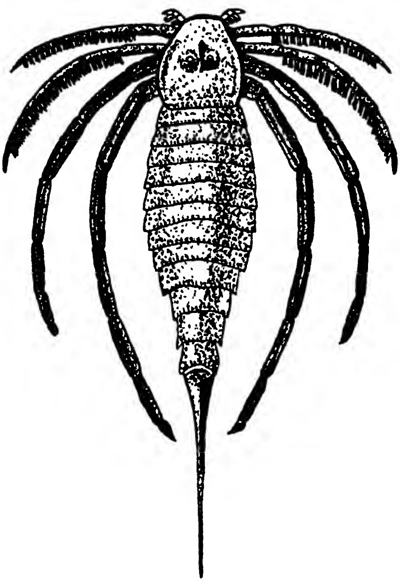


FIG. 208.—*Stylonurus*, a Late Devonian eurypterid about 5 feet in length, from New York. (*After Goldring, from Ruedemann and Clarke.*)

The most primitive and one of the most important orders of Late Paleozoic insects is the Palaeodictyoptera, characterized by the very archaic structure of the wings which have a type of venation matching almost exactly the hypothetical ancestral insect wing. To this group belong the first definitely known insects, which occur in rocks of Early Pennsylvanian age. Supposed insect specimens that have been reported from Silurian and Devonian rocks are not authenticated. Before the extinction of the Palaeodictyoptera in the Permian, the order gave rise to several transitional stocks which in turn introduced existing orders.

The cockroaches (Blattoidea), though contemporaneous with many members of the Palaeodictyoptera, are clearly derived from this order, as shown by wing characters. They were the most common type of insect in the Pennsylvanian period (some eight hundred species) and are numerous in the Permian. The order did not die out at the close of Paleozoic time but, on the contrary, has persisted to the present day, taking rank as the oldest existing insect group that is represented by fossils. In view of antiquity of ancestry and ancient importance in size and numbers, the lowly and despised modern cockroach is really entitled to hold his head high among insect associates.

The Pennsylvanian dragon flies are assigned to a more primitive order than that to which the living representatives of this group belong, the

difference being mainly in wing structure. About a dozen fossil species are known.

The chief Pennsylvanian insect localities in North America are found in Pennsylvania, Illinois, and Kansas. A very famous collecting place in Europe is in beds of Upper Pennsylvanian age at Commentry, France. The most remarkable occurrence of Paleozoic insect fossils yet found in the world is in Lower Permian strata a few miles south of Abilene, Kans. A total of about five thousand specimens have been collected here. Very much has been learned from them concerning the early differentiation and evolution of the insects.

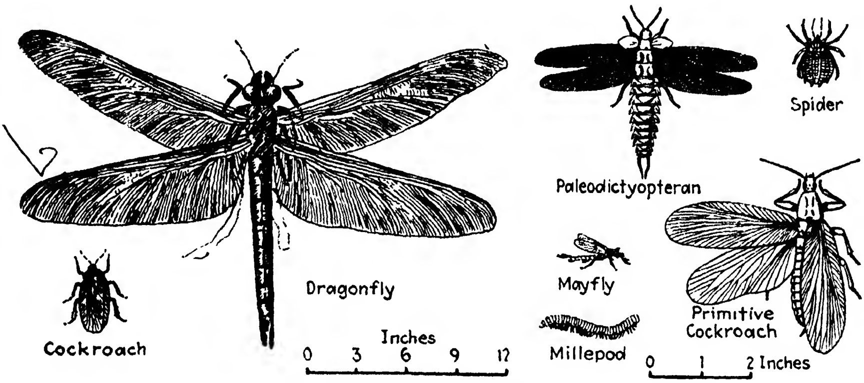


FIG. 209.—Some Pennsylvanian and Permian types of insects.

Fishes

The Devonian period is often termed the "Age of Fishes." This does not mean that fishes reached the peak of their career at this time or that they exceeded in number and variety other kinds of life. Rather, for the first time fishes became well represented in the fossil record, and, because of their great advancement in the evolutionary scale over any of the invertebrates, they may properly be termed the dominant animals of the period. The fishes undoubtedly originated very early in the Paleozoic or before, for fragments of skeletons are known in Silurian and Ordovician rocks. They are the first animals with cartilaginous or bony internal structures, a central nervous system, and other specialized characters that distinguish the vertebrates. For this reason and because the higher vertebrates were undoubtedly derived from them, the Paleozoic fishes are of special importance. Neither paleontologic nor embryologic evidence, however, indicates the exact mode of transition from invertebrate ancestral stock to fish, or from fish to amphibian, and we are left to infer relationships from similarities of structure and the geologic order of appearance of these successively higher types of life. To learn the significant things about the Paleozoic fishes we must first note some of the general structural characteristics of this type of animal and then observe briefly the peculiarities shown by the known fossils.

Structural Features of Fishes.—Fishes have the form and general structure that are best adapted to a mobile life in water. The body is typically compressed spindle-shaped, and streamlined to offer minimum resistance to motion. The head, which is fastened to the body without a neck, bears the eyes, mouth, and gills. The sharks and lampreys have a series of separate openings for the gills that are exposed on each side, but in other fishes these are all covered by an operculum. The body is generally covered by a shingle-like covering of scales, but it may be armored by bony plates, by a flexible covering of quadrangular enamel-like plates, by small toothlike structures embedded in the skin, or it may have only a leathery skin.

Fins, which enable the fishes to swim easily, may be classed in two groups: (1) the unpaired fins, which are median projections from the

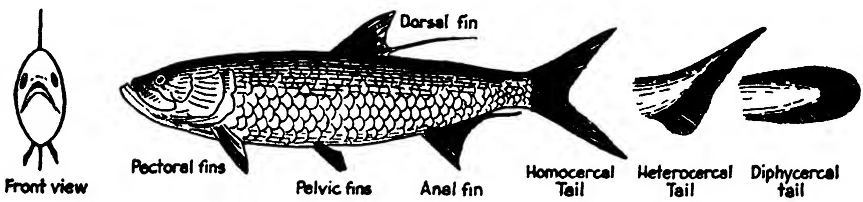


Fig. 210.—A modern fish showing streamlined body and arrangement of fins. Types of tail fins.

back (dorsal fin), tail (caudal fin), and venter (anal fin), (2) the paired fins, which consist of pectoral fins, located one on each side near the head, and the pelvic fins, located typically farther back but in front of the anal fin. Three types of tail fins are observed: (1) *diphycercal*, which extends symmetrically and evenly around the end of the vertebral column, (2) *heterocercal*, in which the end of the vertebral column is bent upward (or rarely downward) and the arrangement of the fin is unsymmetrical, and (3) *homocercal*, a more or less fan-shaped symmetrical tail fin that is developed at the abrupt termination of the vertebral column. The fins are supported near the base by cartilaginous or bony structures and farther out by horny rays or, in the paired fins of certain species, by a skeletal structure that suggests the limb bones of higher vertebrates.

The lungfishes possess an internal organ of respiration. This is absent in other fishes, but the higher types (bony fishes) have instead an *air bladder* that functions as a hydrostatic organ.

Kinds of Fishes.—Several different classifications of the fishes have been proposed, the differences in grouping being due to uncertainty as to the significance and relationships of various structures. Present knowledge favors recognition of three main classes: ostracoderms, selachians, and "bony fishes."

1. *Ostracoderms* (*Ostracodermi*) are a primitive, mainly Paleozoic stock, characterized especially by the shelly plates that encase the body. No trace of internal skeletal features is preserved in the majority of these

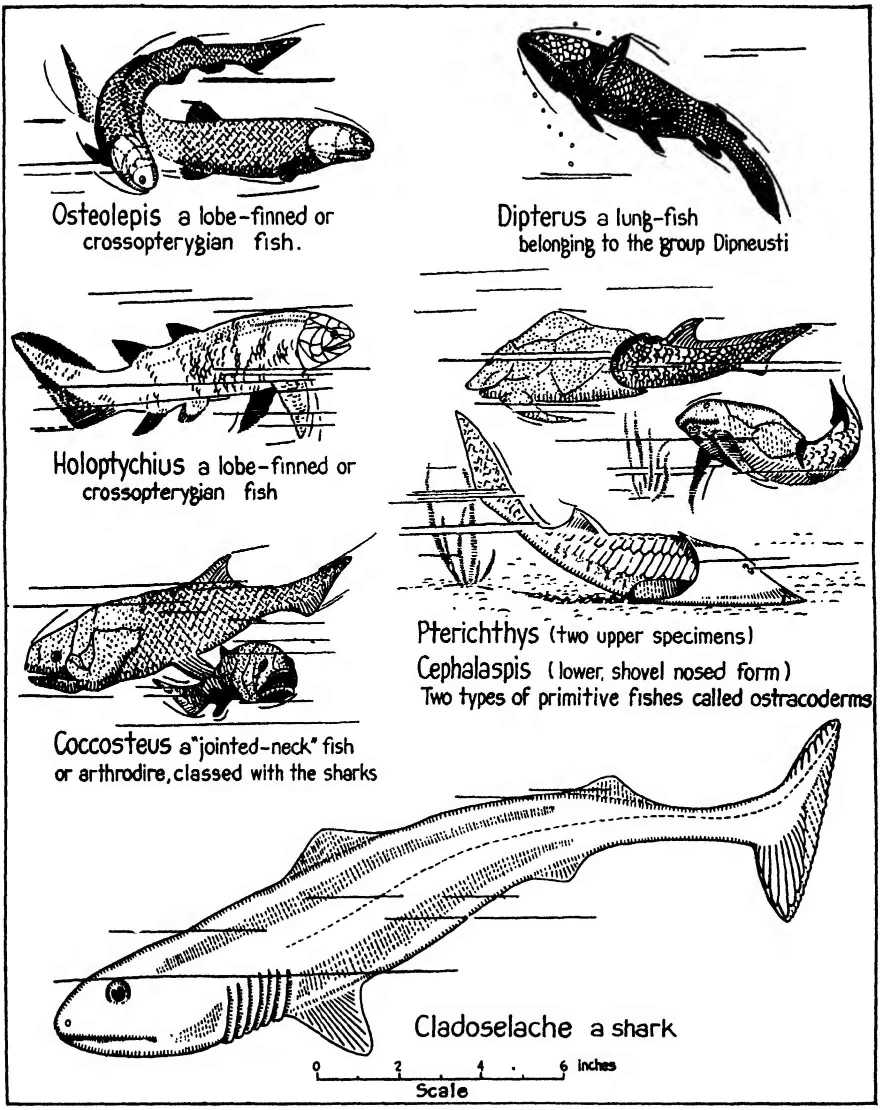


FIG. 211.—Types of Devonian fishes.

fishes, but the outer covering of bony plates is shown. One type (*Pterichthys*) has paddle-like flippers, but there are no true paired fins. The ostracoderms are all small creatures, measuring only a few inches in length. They first appear in Upper Ordovician rocks, show increased

numbers in Silurian beds, and attain maximum development in the Early Devonian formations.

A modern group that is now regarded as a degenerate, armorless descendant of the ancient ostracoderms includes the cyclostomes (*Cyclostomi*). These are jawless, permanently gaping round-mouthed fishes of eel-like form, without paired fins or a scaly or bony covering of the body. They have a primitive diphycercal type of tail fin. The Old Red sandstone of Scotland has yielded a small fossil (*Palaeospondylus*) of this type, but there is doubt as to whether it is actually a cyclostome.

2. *Selachians* (*Selachii*) comprise the sharks and rays. The skeleton is cartilaginous, but the body covering consists of a multitude of hard granules or minute spiny plates that have exactly the same structure as teeth. Well-developed paired fins occur and the tail fin is generally heterocercal. An air bladder or lungs are absent. Fossil remains consist of the dermal covering, spines, teeth, and occasionally the complete body impression. One type of Late Paleozoic sharks bore prominent bony spines which supported the fins. Some of these spines are more than 2 feet long and very massive bony structures, indicating fishes of large size. Shark teeth are frequently found in the marine strata of the Devonian and Mississippian periods, less commonly in the Pennsylvanian and Permian. Most of the Devonian shark teeth are sharp-pointed, but the dominant kinds of later Paleozoic time have broadly rounded wearing surfaces, adapted for crunching shells and for grinding rather than cutting. Commonly there are many teeth in the mouth of a single fish, and they may fit together to form a well-knit pavement.

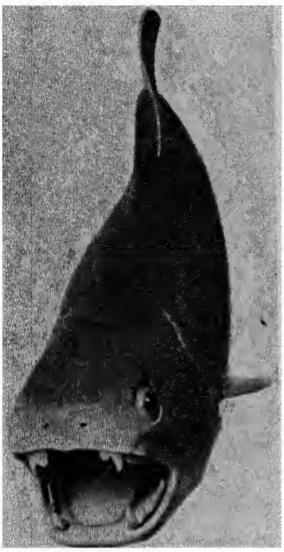


FIG. 212.—Front view of a restoration of the Devonian "terrible fish" *Dinichthys* which attained a length of 20 feet. (*American Museum of Natural History.*)

A group of "jointed-neck" fishes called *Arthrodira* appears, according to recent studies (Stensio), to belong with the sharks. The arthrodires are distinguished by a heavy bony armor encasing the front part of the body, by the powerful jaws, and—a rare peculiarity among fishes—by a joint behind the head that permitted a vertical, hingelike movement. These fishes occur both in stream-laid deposits of the land and in marine strata far from existing shores. Some of the latter, notably the "terrible fish" (*Dinichthys*) from the Mississippi Valley region, were very large, having a head more than 3 feet long and a total length of about 20 feet. They lived throughout the Devonian and into Early Mississippian time.

3. *Bony fishes* (*Ostreichthyes*) include the higher types of fishes with bony skull structure, lungs or air bladder, well-developed fins, and a body covering of scales. Unlike the sharks, the gill openings are covered by an operculum. Three subclasses may be recognized, the first two, in which the skeleton is only partially ossified, being especially important in the Late Paleozoic, and the last, with completely ossified skeleton, best developed in Mesozoic and later time.

a. Lungfishes (*Dipneusti*) are a most interesting group that is first known in the Devonian continental deposits. The few modern examples have an internal cellular sac that functions as a respiratory organ, supplementing the gills and enabling these fishes to survive periods of dryness when stagnant pools of foul, unoxygenated water make life for ordinary fishes impossible. There are three existing genera of lungfishes,

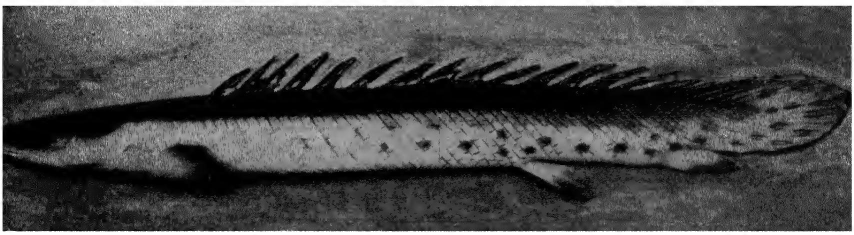


FIG. 213.—*Polypterus*, a modern lungfish from tropical Africa. (*Ward's Natural Science Establishment*.)

living respectively in Australia, Africa, and South America, and it is known that some of these can endure almost complete desiccation. They burrow into the mud, form a sort of cocoon of hardened mucus, and live for months surrounded by bricklike dried clay. When the next rainy season releases them, they are as lively as ever. The Devonian lungfishes were very similar to these modern types and they were undoubtedly evolved as a result of the struggle to survive in the unfavorable surroundings of sluggish and periodically drying streams on the land. Though some living lungfishes attain a length of 6 feet, most of those known from the Devonian are less than a foot long.

b. Lobe-finned fishes (*Crossopterygii*) are distinguished chiefly by the limblike appearance of the pectoral and pelvic fins which have a fleshy middle portion supported by bones that bear homology to the skeletal limb structure of land vertebrates. The tail is diphycercal or heterocercal. The body covering consists of scales of the so-called ganoid type, which have a bony lower layer and a superficial layer of shiny enamel. The teeth are conical in shape and in many cases show the peculiar complexly folded "labyrinthine" internal structure seen in the Paleozoic amphibians. It is probable that these fishes, which are known from the Middle Devonian to Cretaceous rocks, possessed

lungs essentially like those of the "lungfishes." Altogether, it is concluded that this type of fish is most nearly related to the amphibians and higher vertebrates and is most likely to have been their progenitor.

c. *Ray-finned fishes* (*Actinopterygii*) are distinguished by the structure of the fins and by the thoroughly ossified skeleton of the majority of representatives. The scales are of the "enamel-scale" (ganoid) type in some of the more primitive ray-finned fishes but are thin and flexible in the more modern forms. In this group belong the teleosts or true bony fishes, which comprise about 99 per cent of existing species of fishes. They are the most highly organized fishes and are equally adapted to life in the seas and in the waters of the land. They are descendants of the ganoid actinopterygians, of which the earliest known representatives occur in Middle Devonian rocks. Teleosts are first known definitely in Triassic beds but did not become common until Cretaceous time.

FIG. 214.—Cast of footprint from Upper Devonian rocks in northeastern Pennsylvania. The three-toed animal (*Thinopus*) that made this track is probably an amphibian. (*Peabody Museum, Yale University.*)

Amphibians

The first known land vertebrates appeared in Late Paleozoic time, the most ancient fossil indication of this class being footprints of a three-toed animal (*Thinopus*), doubtless an amphibian, in Upper Devonian rocks of Pennsylvania. The amphibians belong next above fishes in the evolutional scale. Modern amphibians include animals that live in water a good deal or all of the time (salamanders, sirens, newts, mud puppies) and also animals that are exclusively air breathers in adult life (frogs, toads).

Amphibians resemble the fishes in living for a part or all of their lives in water, and breathing by means of gills, in being cold-blooded, in the possession by some forms of a diphycercal tail fin, in the presence of a body covering of scales in many of the fossil species, and in the nature of their eggs and the way these are laid in water without further attention from the parents. They differ from fishes in having legs with fingers and toes (although in some amphibians one or both pairs of limbs have been lost), in the possession by the majority of species of functional lungs which make them independent of water as a surrounding medium in adult life, and in the structure of the heart, the mobile muscular tongue, and other features. As already noted, the amphibians were probably derived from crossopterygian fishes.

Stegocephalians.—The Paleozoic amphibians differ especially from those of the present day in the presence of a covering of plates on the head that in the larger forms was a heavy bony armor. Accordingly, they are commonly called stegocephalians, the name meaning "covered or armored head." All of these amphibians had relatively flat, generally

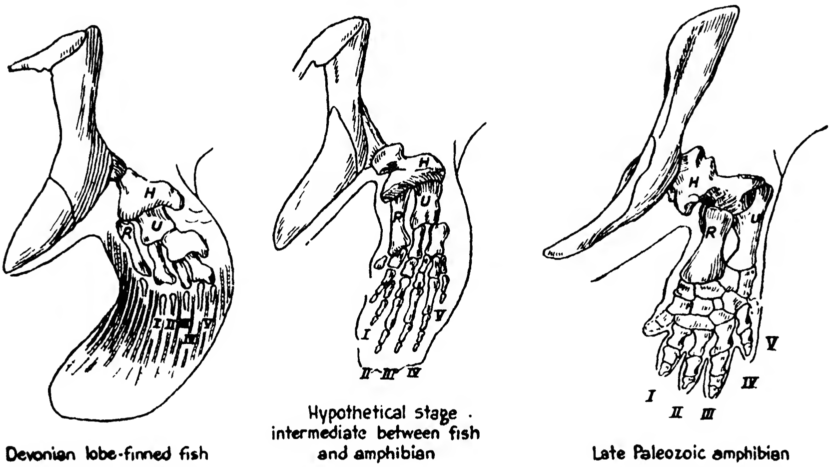


FIG. 215.—Drawings showing probable mode of evolution of the limb structure of amphibians and higher vertebrates from the paddle of lobe-finned fishes. (*W. K. Gregory, from K. F. Mather, Sons of the Earth, W. W. Norton & Company, Inc.*)

broad heads with eyes directed upward, and the mouth very wide. A more or less well-developed tail is invariably present. The early, more primitive types were animals with short, weak legs and laterally flattened tails that functioned as an aid in swimming. Some of the Paleozoic amphibians were only an inch or two in length but there were also very primitive forms as large as a crocodile. There was a considerable variety

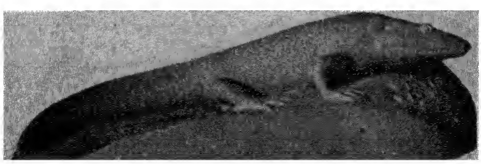


FIG. 216.—A small salamander-like Pennsylvanian amphibian (*Diplovertebron.*) (*Field Museum of Natural History.*)

of these animals in Pennsylvanian and Permian times. Some were ponderous and evidently very sluggish, waddling about in a slow, lumbering fashion; others were active, lizard-like creatures with lighter bodies and well-developed limbs; some were probably very capable swimmers; and a few were entirely legless, snakelike forms. The stegocephalians lived in the fresh waters and on the lands. Probably most of them were

carnivorous, judging by the nature of the teeth, feeding on invertebrates, small fishes, and other amphibians.

One of the most prominent groups among the stegocephalians is that of the *labyrinthodonts*, so called on account of the intricately infolded

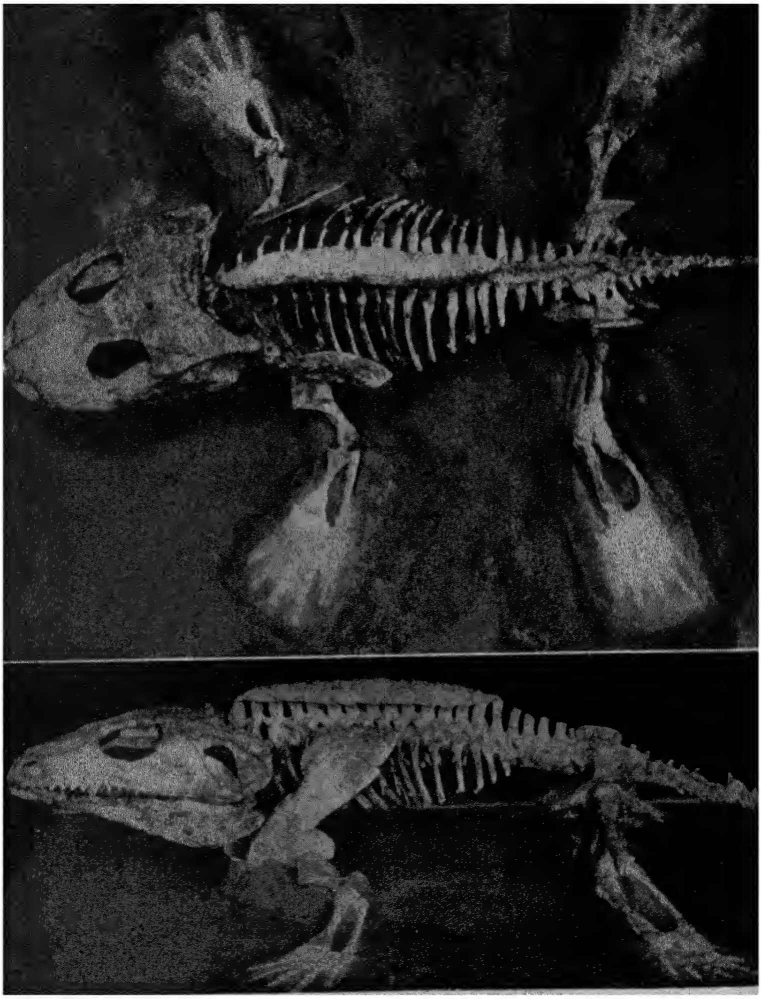


FIG. 217.—A short-bodied Permian amphibian (*Cacops*) with bones of the back fused together. The opening for the pineal eye may be seen in the upper figure slightly behind and midway between the eye orbits. (*Walker Museum, University of Chicago.*)

structure of the enamel in the teeth. This peculiarity was noted in Devonian crossopterygian fishes. The labyrinthodonts attained the maximum size among amphibians, some having a broad, bony head 4 feet long and a total length of about 15 feet. The skull in these animals

was unusually heavy and solid, and the breast was covered by three large and thick bony plates.

An interesting feature which is shown very clearly in the Paleozoic amphibians is an opening on the top of the skull behind and midway between the eye orbits. This marks the position of a third eye, the so-called pineal eye. The aperture occurs also in the crossopterygian and other primitive fishes, in many fossil reptiles, and in one living species. As a vestigial organ, this eye is present in all higher vertebrates, including man.

The stegocephalians probably originated in Devonian times. Skeletal remains are known in rocks of Mississippian age in Europe but in America

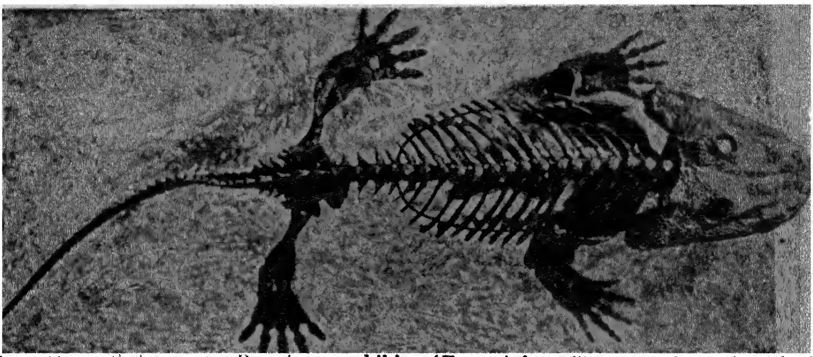


Fig. 218.—Skeleton of a Permian amphibian (*Eryops*) from Texas. This animal had a thick bony skull that in large specimens measures 2 feet in length and 18 inches in width at the back. The entire length of this amphibian ranges up to nearly 10 feet. (*American Museum of Natural History.*)

they have not as yet been found in beds older than Pennsylvanian. In this period, stegocephalians were numerous and highly varied, although most of the fossils come from a very few localities. Some 90 species have been described from the Pennsylvanian rocks of North America. They continued as an important element in the land fauna of Early Permian times, but rapid increase in the number of reptiles pushed them into a subordinate place. Stegocephalians were rare in the later Permian and they disappeared in the Triassic period, being replaced in later rocks by representatives of modern orders.

Reptiles

The most highly developed animals of later Paleozoic time are the reptiles, although it is possible that the beginning of mammals occurred before the close of the era. Reptiles, like amphibians and fishes, are cold-blooded, and in skeletal structure the more primitive reptiles can hardly be differentiated from certain stegocephalians. From an evolutional standpoint, however, the advancement of reptiles over amphibians

is almost comparable to that of fishes over invertebrates. This improvement is seen mainly in the nature and mode of development of the egg. In amphibians and fishes the eggs are necessarily laid in water. There is virtually no stored food material and the almost embryonic newly hatched young are required to fend for themselves. Among reptiles, structures are introduced in the egg which for the first time make the animal independent of water as a surrounding medium during at least the early stages of development. This is accomplished by the presence in the egg of an outer protective covering or shell, but mostly by the development of two membranes within the shell. One of these membranes, the *amnion*, serves as a sort of water bag over the delicate embryo, preventing its drying up, and the other (*allantois*) a sac with numerous small blood vessels that functions as a respiratory organ, the air passing readily through the porous outer shell. Food supply during embryonic growth is supplied by yolk substance within the egg. The significance of these structures is exceedingly great as regards conquest of the lands by vertebrate life, for the reptiles and their descendants, birds and mammals, were liberated from dependence on aquatic surroundings for growth in the egg and first life stages after birth. A few reptiles give birth to the young fully formed.

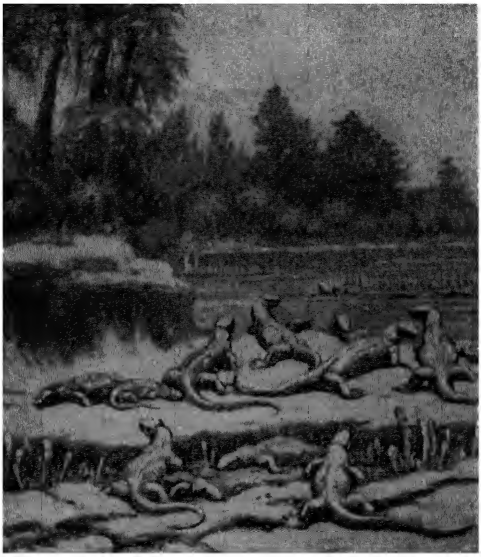


FIG. 219.—A group of lizard-like reptiles (*Casea*) from the Permian of north Texas. These animals attained a length of about 4 feet. (*C. R. Knight, Field Museum of Natural History.*)

The primitive, first-known reptiles in rocks of Pennsylvanian age were very like amphibians, for the limbs were short hardly lifting the squat, plump body above ground. The head was armor-plated like that

of the stegocephalians. The tail was generally long, the hand and foot five-fingered, and the body probably scale-covered but not armored. The teeth were mostly large, sharply pointed, and in some cases distinctly curved backward, of use in catching and holding flesh. Most of the Late Paleozoic reptiles were certainly carnivorous, but in a few the teeth were rounded and blunt.

The amphibian-like Pennsylvanian and Early Permian reptiles (called cotylosaurs) are the stem from which, at about the beginning of Permian time, branched other reptilian types with higher, more lightly built skulls, longer legs, and variously different skeletal characters.

Many of the Early Permian reptiles were evidently sluggish creatures, but others were moderately active. Judging from general form and especially from characters of limbs and teeth, some waddled about along the shallow streams or in swampy places, probably feeding on inverte-

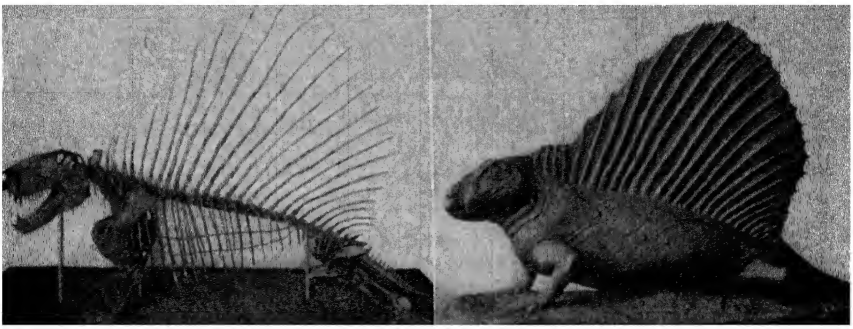


FIG. 220.—Skeleton and restoration of the large fin-backed reptile *Dimetrodon* which attained a length of about 8 feet. (*Skeleton, American Museum of Natural History. Restoration, C. W. Gilmore, U. S. National Museum.*)

brates and grubbing succulent roots and stems. Others suggest the later insectivores. At least one type, with form much like the modern lizard, had well-formed slender limbs adapted for swift running, the leg bones being light and hollow as in birds. Williston thinks that this creature may have been partly arboreal. A few reptiles returned to the open waters to compete with and probably prey upon fishes, perhaps including types like those from which they themselves had descended a few million years before.

Unlike the fishes and amphibians, however, the aquatic reptiles were exclusively air breathers, for no reversion from a higher type of respiratory structure, such as the lungs, to a lower, such as gills, is known in any animals that have once fully attained the air-breathing habit.

The most peculiarly specialized of the ancient Paleozoic reptiles were the fin-backed pelycosaurs (like *Dimetrodon*), some of which attained a length of at least 8 feet. Along the back was a high fin supported by

bony spines of the vertebrae, the longer fin spines being as much as 3 feet high. In the so-called "ship lizard" (*Naosaurus*) these spines bore horizontally projecting prongs that slightly suggest the spars of a square-rigged sailing vessel. Most of these animals were carnivorous and they lived exclusively on land. It is not apparent that the dorsal fin was advantageous for either offensive or defensive purposes. The pelycosaurs first appeared in Late Pennsylvanian time and became extinct before the end of the Permian period.

Another interesting group which is much more important from an evolutional standpoint is the Therapsida, among which are some (especially the group called theriodonts) with teeth differentiated into types almost exactly corresponding to the incisors, canines, and molars of mammals. The skull has a distinctly mammalian appearance which contrasts strongly with that of the ordinary reptile with jaws armed with teeth that are all of the same kind. The first mammals, the oldest known occurring in Triassic rocks, are believed to have sprung from this stock. Other theriodonts gave rise to some of the higher types of reptiles which dominated the lands in Mesozoic time.

LATE PALEOZOIC PLANT LIFE—THE AGE OF FERNS AND SCALE TREES

Until the early part of the Devonian period the fossil record of plant life is restricted to seaweeds of various sorts and other primitive vegetation belonging to the thallophyte class. We now come to a most interesting and remarkable representation of plants that lived on land. In the Devonian is a peculiar group, known as the Psilophyta, which is quite unlike any other class of plants but gives evidence in its generalized characters of ancestral relationships to various later forms of vegetation. And there are ferns of several types and lepidophyte trees, the latter having trunks more than 3 feet in diameter and probably 40 feet tall. The Mississippian and Pennsylvanian periods mark the culmination of this ancient land flora, when there was greatest variety and when maximum sizes in plants of low orders were attained. Many of the shale deposits near coal beds furnish an extremely rich and beautifully preserved record of these plant growths. Permian time is chiefly characterized by the waning or disappearance of the earlier plants, the expansion of early types of conifers, and the development, especially in the Southern Hemisphere, of a cool-climate flora in which certain rather coarse fernlike plants dominated. This was a time of great change leading up to the different-looking floras of the Mesozoic era. There is space in our study for introduction to only the most important types of Paleozoic plants.

The first definitely known land flora comes from the Lower and Middle Devonian rocks of eastern Canada, Maine, Montana, Scotland, and central Europe. This is the Psilophyta group, already mentioned, fossil remains of which were first discovered many years ago by the

Canadian geologist Sir William Dawson. *Psilophyton* was a naked, leafless plant with a woody stem half an inch or less in diameter and fairly numerous branches rising 2 feet or more from the ground (see Fig. 230). The tips of the younger branches twisted in a coil like new fern leaves, and some of the branches bore at the end small, elongate pods or cases containing the reproductive spores. The stems have breathing pores (*stomata*) such as occur in the leaves of higher plants, and the cell structure shows the presence of a vascular system that serves as a means of transmission of water and nourishment derived from the underground portion of the plant. The latter did not consist of true roots but was a

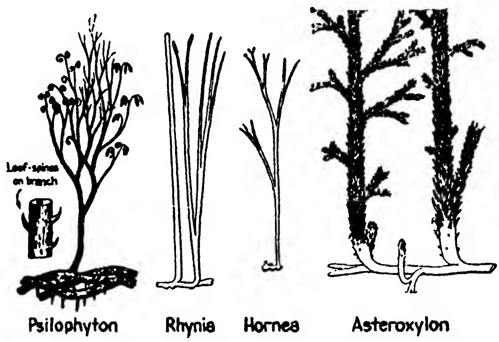


FIG. 221.—Types of oldest known land plants, of Devonian age.

horizontal stem or runner (*rhizome*) bearing small rootlets. In various ways there is indication here of the adaptation of an originally algal type of aquatic plant to a moist environment on the land, and there is a beginning of the all-important structures that enable land plants to thrive.

Recently some interesting discoveries of well-preserved plants (*Rhynia*, *Hornea*) related to that just described have been made in a Middle Devonian silicified peat bed in Scotland. These plants are likewise leafless and they bear spore cases at the tips of the branches. Another type (*Asteroxylon*) was completely covered with tiny, spinelike leaves, however. It resembles the club mosses (Lepidophyta) to be discussed later and may be related to this group which occupied a leading place in the Carboniferous floras.

Ferns (***Pteridophyta***).—Ferns, which are generally distinguished by the form of their leaves with numerous branching leaflets, and by the presence of spore clusters on the under side of leaves or on specialized fronds, are represented by some six thousand living species that range in size from very minute, delicate forms to tropical tree ferns 50 feet high. The spores are produced in almost incredible numbers, a single plant sometimes liberating 20 to 50 millions.

As far as now known, ferns made their appearance in the early part of Devonian time, though the forms attributed to the group are so simple and undifferentiated that they may be nearly equally related to other low orders of vascular plants. *Archaeop-*

teris, a fern with a large pinnate frond, bearing wedge-shaped, obliquely set leaves and oblong spore cases (*sporangia*), is characteristic of the Upper Devonian and is worldwide in distribution. Many of the earlier ferns produced sporangia without rings and find their nearest living relatives in the essentially tropical family Marattiaceae. Some of the fernlike types of Early Pennsylvanian time include climbing plants of tropical aspect, many of which suggest lianas. Others among the climbing forms were of filmy delicacy.

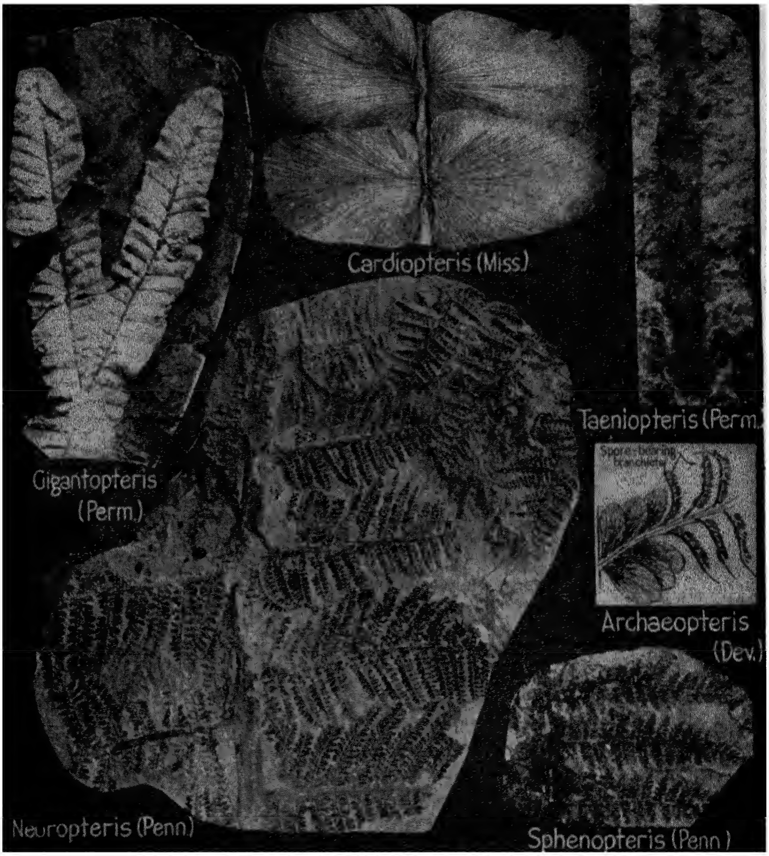


FIG. 222.—Representative types of Late Paleozoic ferns.

In the Pennsylvanian period came the elaboration of a great group of compound fronds typified in the genus *Pecopteris*. The leaves, strikingly similar in form to some of the ferns of the present day, were in some instances very large. Certain leaves of this type found in Upper Pennsylvanian and Permian beds were borne at the tops of long trunks which attained diameters of 30 inches or more. These tree ferns were provided with an extremely thick outer zone of protective and water-storing, rootlike appendages, forming what is known as the ramentum. The fronds of some of the tree ferns, which were as large and beautiful as any now living, were 12 feet in length, and the young fronds unrolled in the fashion of modern ferns. Maximum development of the tree-fern group was attained in the Pennsylvanian period.

Seed Ferns (*Pteridospermophyta*).—Some years ago a very surprising paleobotanical discovery was made when specimens that looked like ordinary ferns and had always been taken for ferns proved to have true seeds instead of spores. Separated seeds are not uncommon in some Carboniferous beds but it was not suspected that any of the ferns belonged with seed plants. Now it is clear that many of these seeds of previously unidentified origin come from the seed fern, and it is possible that some of the fern species known at present only by their foliage may prove ultimately to be seed-bearing and thus not true ferns at all.

The oldest known seed ferns come from Middle Devonian strata of southeastern New York. Some fifty years ago several fossil tree trunks were found in these rocks near the little town of Gilboa. They were recognized as ferns, but not until 1920,

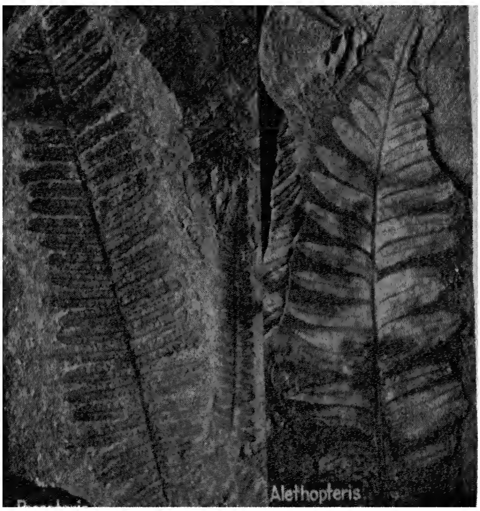


Fig. 223.—Leaves of two common types of Pennsylvanian ferns. (*Charles Butts, Alabama Geol. Survey.*)

when scores of additional specimens, together with foliage and seeds, were unearthed in building a large dam at this place, was it learned that there existed here a veritable seed-fern forest. As many as 18 stumps, 4 or 5 feet tall and 1 to 3½ feet in diameter were found in a space 50 feet square. These seed-fern trees, called *Eospermatopteris* (dawn seed fern), are believed to have grown to a height of about 40 feet, and some of the great leafy fronds at the top were fully 6 feet long (see Fig. 230).

The best-known Carboniferous seed fern is *Lyginopteris*, a fairly common plant in the earlier Coal Measures of both Europe and America. It had a slender stem, 2 inches or less in diameter, and was not nearly so tall as its Devonian predecessor just described. The leaves, up to 3 feet in length, and the seeds were essentially like those of other seed ferns.

This interesting group of plants must have originated some time before the Late Devonian, in which highly developed types occur, and it disappeared before the close of the Paleozoic. Since resemblance to the true ferns is so close that distinction rests solely on the nature of the fruiting organs, it is thought by some that true ferns were

ancestors of the seed ferns, but, if they were, the time of branching-off must have been in the Middle Devonian or earlier.

Scale Trees (*Lepidophyta*).—A dominant and certainly one of the most striking elements in the Late Paleozoic floras was the scale tree or lepidophyte, represented at present by the lowly club mosses and their allies which creep along the ground. In Pennsylvanian time, however, this group was represented by splendid trees more than a

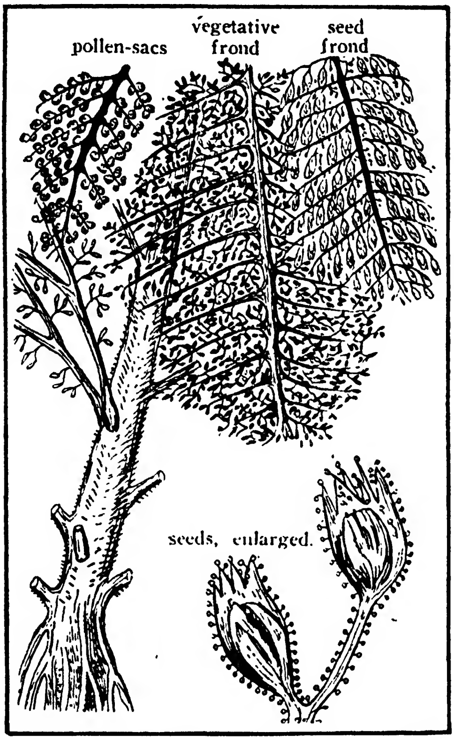


FIG. 224.—One of the best-known seed ferns, *Lyginopteris*, of Pennsylvanian age. (*After Scott.*)

hundred feet in height. The lepidophytes are distinguished by rather short, stiff, scaly or needle-like leaves that cover densely all of the trunk and branches excepting parts from which the old, dead spines have dropped off. The leaves of the large fossil species not uncommonly attained a length of 6 or 7 inches and were sometimes nearly half an inch wide at the base, which was roughly diamond-shaped. The place of attachment of each leaf was marked by a distinctive scar, the form of which varies somewhat in different species. In the trees known as *Lepidodendron*, these scars were arranged in regularly intersecting oblique rows, but in *Sigillaria*, which was also a very important type, the scars were dominantly in vertical series. Leaves belonging to this latter

genus were in some cases much longer than in *Lepidodendron*, exceptionally reaching a length of 3 feet. Some of the Sigillarias were short, stocky, and unbranched, a trunk 6 feet in diameter at the base tapering to the top less than 20 feet above ground. Others were tall and slender. One unbranched specimen 200 feet long is reported. The Lepidodendrons commonly bore branches in the upper part but the branches were far less numerous than in modern trees.

The lepidophytes bear spores which grow in cones, appearing in *Lepidodendron* at the ends of the branches but in *Sigillaria* in a whorl

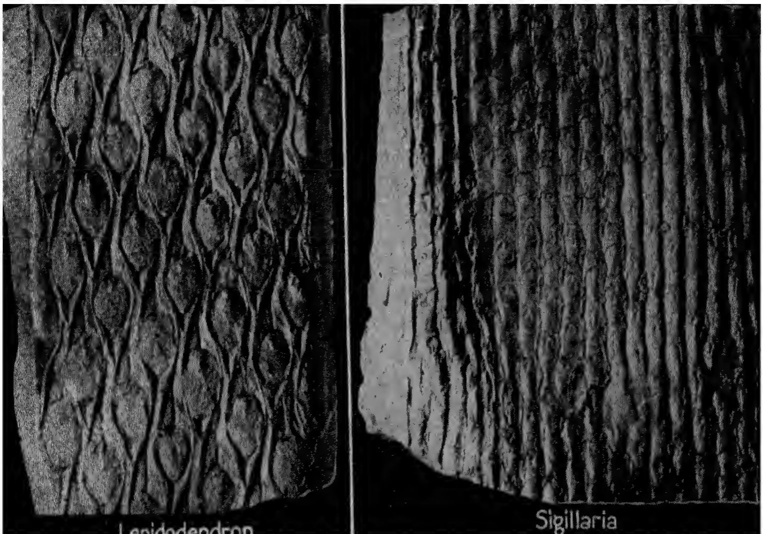


Fig. 225.—A portion of the trunks of common types of great lepidophyte trees that were world-wide in Late Paleozoic time. Note the nature and the arrangement of the leaf scars on these specimens, which are Pennsylvanian types. (*Charles Butts, Alabama Geol. Survey.*)

around the stem or in vertical rows. In the first group some cones reach a length of 20 inches; in the second the maximum is about 12 inches. The cones must have been produced in great numbers to account for the great quantity of spores and spore cases which largely make up the material of certain coal beds (especially the cannel coals). There were large underground parts consisting of rhizome-like roots that successively fork in two. Though rootlike in appearance, they lack true root structure. Small rootlets were attached to them and, because of the circular scars made by these, and underground branches, which cannot be distinguished when found separately from the *Lepidodendron* or *Sigillaria* trunks that they supported, are called *Stigmaria*. Many stumps are found standing in the places where they originally grew.

The history of the lepidophyte trees, as represented by known fossils, begins in the Upper Devonian when a plant called *Protolepidodendron* (first lepidodendron) lived

in western New York, Pennsylvania, and Europe (see Fig. 230). One of the best specimens is a trunk some 18 feet long, tapering from a diameter of 1 foot at the base to 3 inches at the top. When living, it was probably 35 feet or more tall. The leaf scars on the lower part of the trunk are like those of some kinds of *Sigillaria*, but on the upper portion of the tree they were more like those of *Lepidodendron*. In the Mississippian and Pennsylvanian periods this group expanded enormously, not only becoming one of the most common and widespread types of plant life but developing into several scores of different species. The trunk of a giant *Lepidodendron* of Mississippian age found in an English coal mine measured 114 feet up to the first branches and the crown extended at least 20 feet higher. Many of the Pennsylvanian species had trunks up to 4 feet in diameter and were probably more than 100 feet tall when living. *Lepidodendron* is reported to have lived on into the Permian and *Sigillaria* is represented in the Early Triassic by *Pleuromeia*. It disappeared before the end of this period.

FIG. 226.—Coalified stump of a lepidophyte tree standing in the position of growth. (*U. S. National Museum.*)

Horsetail Rushes (*Arthrophyta*).—The so-called horsetails are plants with numerous unbranched, hollow, jointed, and ribbed stems. Most of the modern species, about 25 in number, are less than 3 feet tall but one in South America has stems an inch in diameter and 30 to 40 feet tall. This group was very well represented in the Carboniferous and Permian floras of all parts of the world, the trunks being generally known as *Calamites*. Most of these ancient horsetails were very much larger than their living descendants, some attaining a diameter of 3 feet and a height of fully 100 feet. They occur mainly as flattened impressions and as sandstone molds of the hollow stems. The upright trunks grew from a prostrate, horizontal stem and it is evident that they thrived in wet or swampy sandy soils. At the nodes along the stem were branchlets, often arranged in whorls, and these bore circlets of leaves (*Annularia* or *Asterophyllites*) at their nodes. Reproduction was carried on by means of spores that grew mostly in long narrow cones. Probably there were many jungle-like areas of these calamites, resembling on an enlarged scale the dense southern canebrakes, and comparable to the bamboo thickets of today.

The Pennsylvanian and Permian are characterized by the presence of an interesting and unique order known as the *Sphenophyllales*. They embrace angular jointed and irregular branching stems bearing verticils of wedge-shaped leaves, generally six to the joint, in the upper part of the plant. The stems included a large central solid triangular axis

built up from the angles; the fruit consisted of small slender cones in which the sporangia were arranged in rows on the axils or on the upper surface along the midrib of the slender pointed bracts. It has been thought by many that *Sphenophyllum* was a strictly aquatic plant, but on account of its structural features this has been questioned (Fig. 84).

Cordaites.—Another conspicuous Late Paleozoic plant is an unfamiliar tree known as *Cordaites*. It was distinguished by a tall, slender trunk, rarely 2 feet in diameter but 30 to 100 feet high. Branches occurred only near the top and they bore a thick mass of leaves which in some

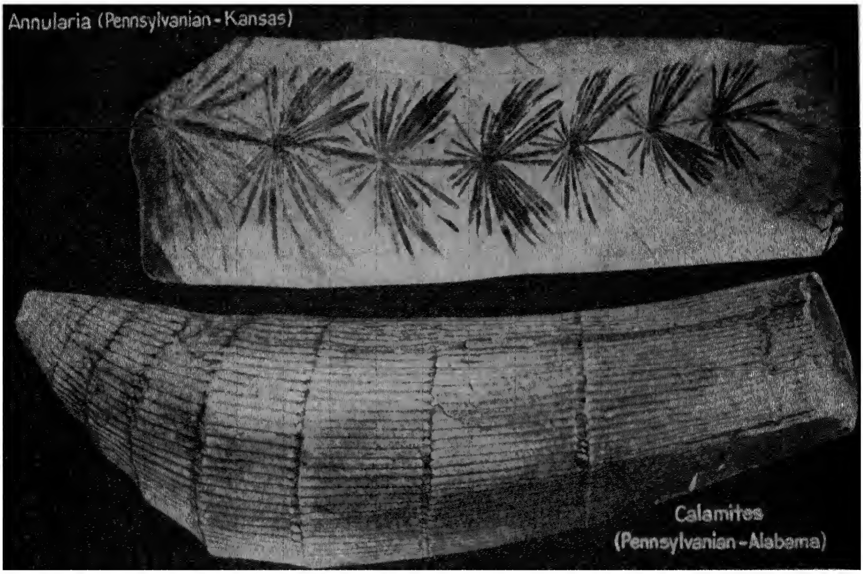


FIG. 227.—Stem and leaves of Pennsylvanian horsetail rushes. The stem here shown is really the sand filling of the hollow interior of the plant and it is therefore an internal mold. (*Charles Butts, Alabama Geol. Survey.*) The circlets of leaves, as shown at left, grew outward from the nodes of the stem. (*M. K. Elias, Kansas Geol. Survey.*)

species were strap- or paddle-shaped, round-pointed, and up to 3 feet long, and in others short or fan-shaped and 15 inches wide. In the center of the trunk was a wide pith cavity, the woody part outside being made of long, thick-walled cells that show little or no development of growth rings. This indicates that the climate in which the cordaites lived was equable, without strongly contrasting seasons such as prevail in cool temperate regions. The cordaites were seed-bearing plants that are undoubtedly related to seed ferns, cycads, and modern conifers. They were exceedingly widespread in the Carboniferous and Permian of both hemispheres. Rarely, they were locally so abundant that certain coal beds are composed almost exclusively of their remains. Continuing into the Permian, they mostly disappeared before the end of the Paleozoic, but a few survivors are known in the Triassic period.

Conifers (***Coniferophyta***).—The conifer group, represented abundantly in post-Paleozoic geologic history and in modern times by the pines, spruces, firs, and many other trees, was represented by several rather primitive types in the Permian and by a few in the Pennsylvanian. Information concerning these most ancient conifers is, however, rather incomplete. One type, called *Walchia,* had branches with numerous slender branchlets extending out approximately parallel and fernlike in a flat development, all densely clothed with short needle-like leaves. *Walchia* was abundant and very widely distributed in Permian time. About a dozen other probable conifers have been described from late Paleozoic rocks.

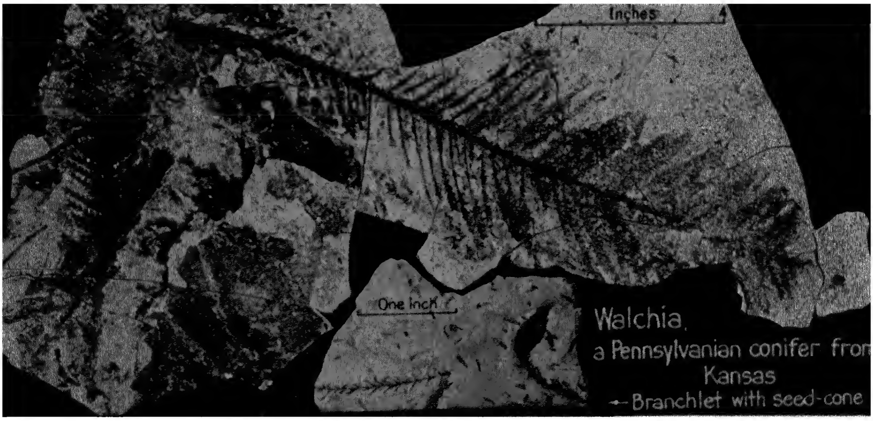


FIG. 228.—Remarkable specimens of conifer branches (*Walchia*) from the Upper Pennsylvanian rocks of Kansas. (*M. K. Elias, Kansas Geol. Survey.*)

The Glossopteris Flora.—The great climatic changes which occurred in Permian time, marked by arid regions and, especially in the Southern Hemisphere, by widespread glaciation, naturally had a profound influence on plant life. In Australia, southern Asia, Africa, and South America the assemblage of plants so characteristic of the Carboniferous of the northern lands practically disappeared, and there developed instead others that were better able to cope with the new environment. A dominant type in this group was a coarse-leaved fern named *Glossopteris* which had a creeping stem and simple undivided leaves, an inch or two to 20 inches long. *Glossopteris* is common in the Permian of most of the Southern Hemisphere. Specimens of it were collected by the Scott Antarctic expedition within a few degrees of the South Pole. The genus survived into the Jurassic period. A less abundant but even more widespread genus which also was distinctive of this Paleozoic flora is *Gangamopteris,* which likewise has coarse, simple leaves, distinguished from *Glossopteris* by their rounder form and the absence of

a midrib. A few lepidophytes and conifers of tree size are associated with *Gangamopteris* in the so-called early Gondwana flora of the Southern Hemisphere.

Climatic Significance of Plants.—The effect of climate and environment on plants of today is more or less familiar to everyone. Moisture, temperature, and the character of the soil are the most important factors in determining the nature of the vegetation in any given place. Accordingly as regards moisture, we recognize, at one extreme, water plants (hydrophytes) like the stonewort (*Chara*) and the waterlily, and, at the other, desert plants (xerophytes) like the cactus which grows only in arid or semiarid areas. The structure and appearance of plants may be modified greatly as a result of this adaptation. As regards temperature, the evident contrast between tropical floras, with palms and numerous other plants that cannot endure cold, and the stunted evergreens, alpine shrubs, and other hardy plant life of arctic or high-mountain districts, needs merely to be mentioned. Many plant species are adapted to intermediate conditions such as prevail in most of the temperate climatic zones. They may stand successfully a cold winter season or alternating dry and wet seasons, growth being retarded in the unfavorable months. This results in development of growth rings in the structure of trunks and limbs, and it is accordingly easy to distinguish a tree that grew under changing seasonal conditions from one that lived in a somewhat uniform climatic environment. Certain kinds of plants have become so adapted to these different types of surroundings that they require them, and their presence in a given flora may furnish basis for inferences concerning climate. Altogether, the relationship of plants (and animals) to environment is a rather complex subject which the biologist designates as a special field of scientific research (ecology). Fossil plants were certainly affected by climate in about the same fashion as their living descendants and we have, therefore, a clue to ancient climates that supplements and corroborates conclusions based on other lines of evidence.

FIG. 229.—Leaves of *Gangamopteris* and *Glossopteris*. (One-fourth natural size.)

Cold, even frigid, climates during parts of Pennsylvanian and Permian time in the Southern Hemisphere are abundantly witnessed by widespread glacial deposits. The characters of the *Glossopteris-Gangamopteris* flora

likewise indicate a cool climate rather unfavorable for plants. Aridity, which is locally indicated by salt and gypsum deposits that resulted from prolonged desiccation and by associated thoroughly oxidized red sediments, is not ordinarily shown by plants, probably mainly because conditions are very unfavorable for fossilization. We do, however, find leathery, small-leaved, spine-bearing plants that lived presumably in this sort of environment.

The abundant and varied flora of Carboniferous times, including many gigantic trees, is interpreted to signify a moderately warm moist climate that in general lacked pronounced seasonal variation, for growth rings are almost entirely absent from the woody trunks found in many regions, especially in the Early Pennsylvanian. The nearly world-wide distribution of many plant species shows that environmental conditions must have been strikingly uniform over immense areas.

SUMMARY OF LIFE DEVELOPMENT IN LATE PALEOZOIC TIME

Outstanding features of the life of Late Paleozoic time are increased prominence of vertebrates and the appearance of many kinds of land plants. The vertebrates include a variety of marine and fresh-water fishes, but especially important are the first four-legged creatures of the land, the amphibians, and the more highly organized class derived out of them, the reptiles. The land plants are primitive as compared with modern floras but the variety of species is large and some kinds grew to heights of more than 100 feet. Marine invertebrates were quite as abundant and varied as in Early Paleozoic time, although there were changes in the relative importance of different groups.

Devonian Period.—The Devonian period is often designated as the "Age of Fishes" because of the great advancement along many lines that is witnessed by fossil fishes of this period. There are numerous representatives of the shell-encased ostracoderms, various kinds of sharks, the jointed-neck arthrodires, lungfishes, and the enamel-scale crossopterygian fishes. Out of the last-named group were probably developed the first amphibians, and evidence of footprints in Upper Devonian rocks indicates that the beginning of the amphibians belongs as far back as Devonian time.

In so far as the invertebrates are concerned, the Devonian period is characterized by the abundance and variety of corals, by the peak of development of brachiopods, and by the advance of ammonoid cephalopods to a well-defined goniatite stage, characterized by moderately curved and angulated sutures. Trilobites are much less numerous than in the Early Paleozoic subera, but there are some large and highly specialized kinds. Crustaceans of the eurypterid type reach a length of more than 6 feet.

The oldest definitely known land plants are leafless woody stems found in Early and Medial Devonian rocks. Upper Devonian strata contain tree ferns with very large fronds, seed ferns, and primitive scale trees. A forest of seed-fern trees is known from numerous stumps in southeastern New York.

Mississippian Period.—There were many fishes, especially sharks, in Mississippian time. Amphibians lived in waters of the land, and among them were the first of the stegocephalians, characterized by the heavy bony armor of the head.

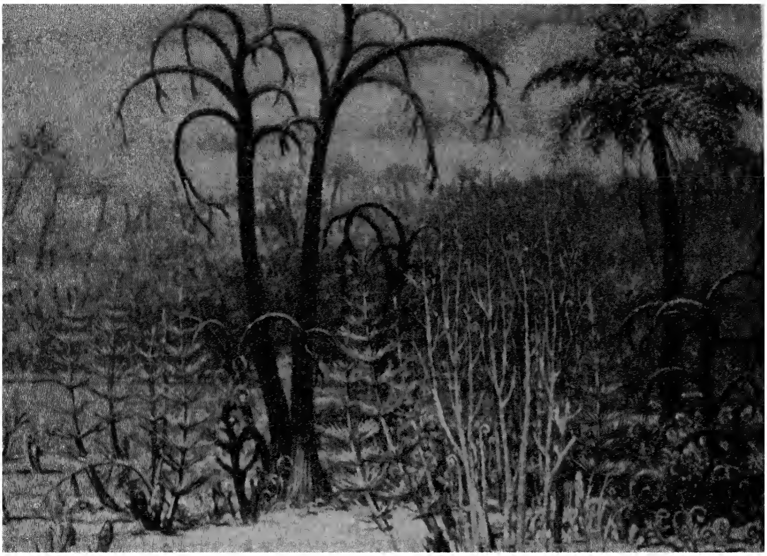


FIG. 230.—A late Devonian landscape in New York.

The seemingly bare-limbed tree with curving branches is the earliest known lepidophyte tree, *Protolepidodendron*. Small scalelike leaves clothe the trunk and branches. The tall palmlike tree at right is the "dawn seed fern" *Eospermatopteris*. In the left foreground are horsetail rushes, *Calamites*, and near the center foreground is a clump of *Psilophyton* with curled tips of the branchlets. (*C. R. Knight, Field Museum of Natural History.*)

Crinoids of the camerate group, distinguished by the proportionately large size of the calyx, culminated explosively in the Medial Mississippian epoch and rocks of this age are especially characterized by prominence of these fossils. Blastoids, also, became very abundant in Mississippian time and then virtually disappeared. There are very many kinds of bryozoans, especially of the delicate lacy type (fenestellids), and a number of peculiarly specialized kinds like the screw-axis *Archimedes* are known. Among brachiopods, which were still very numerous, the appearance of *Productus* and closely allied genera is noteworthy, because shells of this group dominated shallow-water faunas of the world in Mississippian, Pennsylvanian, and Permian time. Trilobites are reduced to an insignificant element in the marine life.

Land plants of Mississippian age include a large number of ferns, scale trees, horsetail rushes (calamites), and the trees called cordaites. The flora is intermediate in character between that of the Late Devonian and the culminating development of Late Paleozoic land plants during Pennsylvanian time.

Pennsylvanian Period.—Large and small amphibians are dominant land animals of the Pennsylvanian period, the stegocephalians being

FIG. 231.—A Permian landscape in north central Texas. The animals in the view are the amphibian *Eryops*. In the left foreground are horsetail rushes, *Calamites*. The tree at right is a *Sigillaria*.

the most important group. There are also primitive, amphibian-like reptiles.

The invertebrate faunas of Pennsylvanian age are similar in general constitution to those of the preceding period except that camerate crinoids are absent and blastoids do not occur much above the base. Among protozoans there is the introduction of the "wheat-grain" fusulinids which include many species and an amazing richness in numbers. Bryozoans and brachiopods are abundant, the latter containing especially an abundance of productids. There is a great advancement in the complexity of suture pattern in the ammonoid cephalopods which are adapted to serve as guide fossils for various zones. Cockroaches are a leading group of insects.

The plant fossils of Pennsylvanian age give a remarkable picture of land vegetation, especially of the lowland swampy areas in which the many coal beds were formed. Of nearly equal prominence are the great scale trees (chiefly *Lepidodendron* and *Sigillaria*) and the ferns, including seed ferns. Calamites and cordaites grew to a height of more than 100 feet in some cases. The first of the conifers occur here. The flora is a very rich one, and it is much the same in the Old World and the New, and in high latitudes and low.

Permian Period.—Stegocephalian amphibians continued to be important in the land life of Permian time but the most important place was now occupied by the reptiles. There were many different kinds of reptiles, some of which show considerable specialization. One group shows characters that are very suggestive of the mammals, and it is

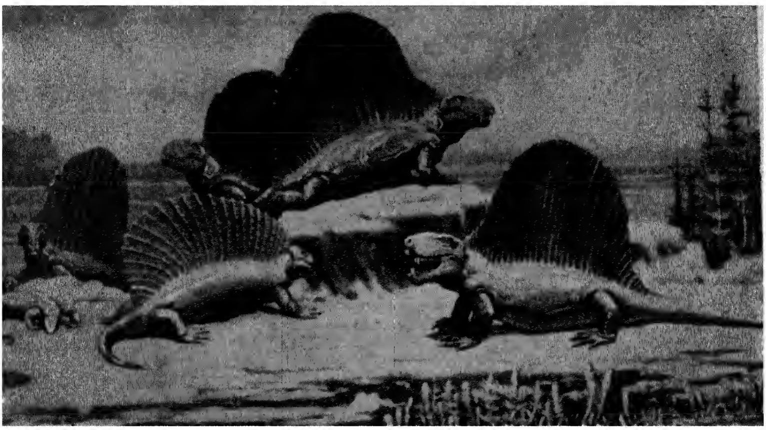


FIG. 232.—Fin-backed reptiles termed pelycosaurs, from the Permian of north Texas. The individual in left front is the "ship lizard" *Naosaurus*. The others are *Dimetrodon*. (*C. R. Knight, Field Museum of Natural History.*)

likely that the first of the mammals may date back to Paleozoic time. The chief localities for Permian fossil reptiles are northern Texas and South Africa.

The invertebrates of Permian time include the end products of various Paleozoic groups and also certain of the stocks that with various modifications lived on into the Mesozoic. In the Permian period occur the last of the fusulinid protozoans, blastoids, and trilobites, and all or practically all of the Paleozoic types of crinoids, corals, echinoids, bryozoans, and brachiopods. Gastropods and pelecypods include long-ranging types that persist with little change into the Mesozoic, and cephalopods with increasing complexity of suture patterns foreshadow the remarkable differentiation of ammonites of Triassic and succeeding Mesozoic time. A wonderful array of Permian insects showing the beginning of many

lines of evolution represented by existing families is obtained from Kansas.

The Permian plants are less varied than those of Pennsylvanian time and they afford evidence of climatic conditions that were generally less favorable for plant growth. Both coolness and dryness are indicated. The widespread distribution of the *Glossopteris* flora in the Southern Hemisphere is noteworthy.

THE MESOZOIC ERA

CHAPTER XXI

THE MESOZOIC FORMATIONS

Study of the Mesozoic portion of earth history may be introduced advantageously by a brief survey of the general nature of the Mesozoic formations in North America and the other continents, the chief regions of surface distribution of Mesozoic rocks, and the important characteristics of these regions. We shall thus gain a conception of the broader features of Mesozoic geology and provide geographic setting for a more detailed consideration of the individual systems.

The lithology of the Mesozoic rocks, taken as a whole, is not strikingly dissimilar from that of the Paleozoic systems. Hard limestones are, in general, less prominent, and the degree of compaction and consolidation of the Mesozoic sedimentary materials is perhaps somewhat less pronounced. The conditions of marine and nonmarine sedimentation were, nevertheless, essentially the same. Distinguishing features of composition, texture, color, and mode of weathering are ready means of identifying the Mesozoic deposits in various regions, when one is familiar with them. The all-important distinguishing character of Mesozoic rocks, however, is the nature of the fossils that are found in them. Both in the seas and on land the life of this era was so different from that of preceding and succeeding parts of earth history that the paleontologist is able to recognize the geologic age of formations easily and definitely. The only exception to this statement lies in certain doubtful or debated horizons near the upper and lower boundaries of the Mesozoic sequence of beds.

MESOZOIC FORMATIONS OF NORTH AMERICA

Distribution.—Outcrops of Mesozoic rocks appear in eastern North America, at or near the coast line, from Nova Scotia to Alabama. The areas of exposure are discontinuous, elongate narrow patches or belts that locally touch the sea in the north but that southward lie at the inner margin of the Coastal Plain or, in part, occur within the borders of the adjacent Appalachian Piedmont.

Upper Mesozoic formations appear at the inner margin of the Gulf Coastal Plain in the southern United States, but outcrops of Lower Mesozoic rocks are not known. All of the Mesozoic systems are repre-

sented in Mexico, their outcrops covering altogether a large portion of the country.

Mesozoic rocks are not known in the eastern or central parts of the Mississippi Valley region or in the Prairie Plains bordering the Great

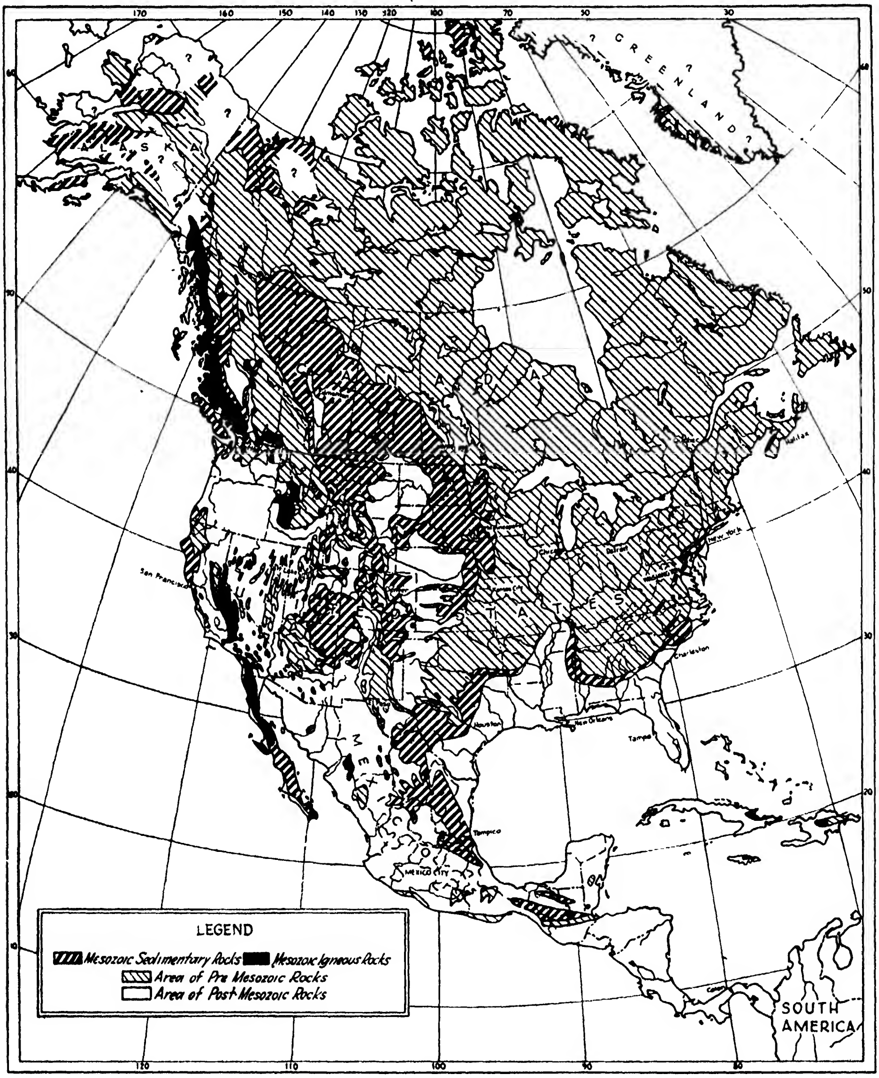


FIG. 233.—Map of North America showing the distribution of Mesozoic outcrop areas.

Lakes, but the High Plains region east of the Rockies is mostly underlaid by Mesozoic formations. Eastern New Mexico and Colorado and the territory extending from western Kansas to far northwestern Canada contain Cretaceous outcrops totaling some hundreds of thousands of

square miles. From the standpoint of breadth of outcrop, this is the chief Mesozoic area of the continent.

The Rocky Mountains region, with which the Colorado Plateaus may be included, also contain extensive Mesozoic outcrops. Because of folding, however, or in some cases because of great topographic irregularities, the outcrop belts are narrow and in part very irregular.

Finally, we may note that Mesozoic formations are prominent along the Pacific Border from the peninsula of Lower California to Alaska. These rocks have been much disturbed by folding and faulting in most places, and accordingly the outcrops occur typically in discontinuous, elongate belts. The exposures occur chiefly in the Sierra Nevada-Cascade and the Coastal ranges.

General Character of Mesozoic Outcrop Areas

Atlantic Border.—The Mesozoic sedimentary rocks of the Atlantic Border region offer slight resistance to erosion and consequently form

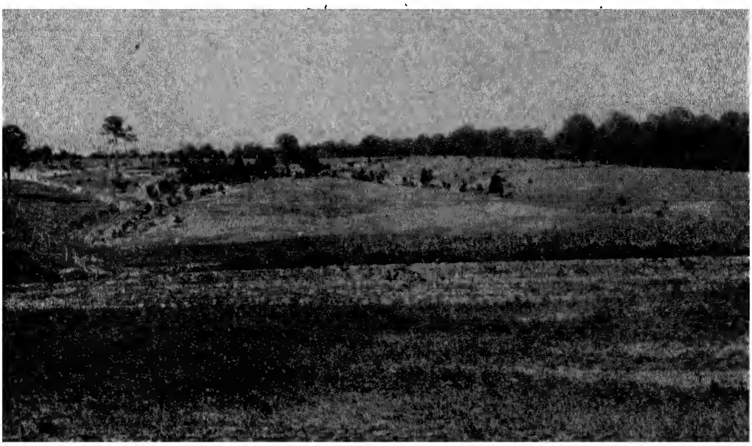


FIG. 234.—A typical part of the Atlantic Coastal Plain. (*U. S. Geol. Survey.*)

lowland plains. Typical examples in areas of Triassic rocks are the Connecticut Valley, the lowland extending from the west side of the Hudson opposite New York City across northern New Jersey, southeastern Pennsylvania, and part of Maryland into Virginia, and other valleys in Virginia and North Carolina that trend roughly at right angles to the general course of the Atlantic drainage. Older rocks, mostly of pre-Cambrian age, largely or entirely surround the Triassic valleys. A noteworthy feature of the Triassic lowlands is the common occurrence of even-topped hogback ridges that are made by sheets of hard igneous rock between the sedimentary layers. The even crest of the ridges is a mark of former peneplanation.

Late Mesozoic (Cretaceous) formations compose the inner border of the Coastal Plain across central New Jersey and parts of Maryland, Virginia, the Carolinas, and Georgia. The contrasting characters of the weak Mesozoic strata of the Coastal Plain and the hard, ancient rocks of the adjoining Piedmont district on the west, make a topographic boundary that, as has been previously noted, is clearly defined in many places. It is called the "fall line," because east-flowing streams have a rapid fall in this part of their course. There are places, however, in which the inner boundary of the Coastal Plain is not at all sharply defined.

Gulf Coastal Plains.—The Gulf region includes Mesozoic outcrops at the inner border of the Coastal Plain, extending from central Georgia

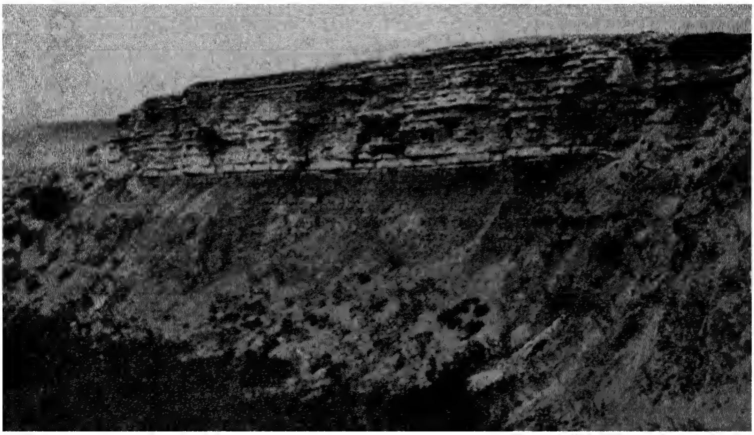


Fig. 235.—Nearly horizontal Mesozoic strata are very widespread in the Great Plains region. Outcrop of Cretaceous limestone (Greenhorn) and shale (Graneros) in southwestern South Dakota. (*N. H. Darton, U. S. Geol. Survey.*)

westward and northwestward to a point near the mouth of the Ohio River. A similar Mesozoic belt crosses part of southwestern Arkansas, southern Oklahoma, and eastern and southeastern Texas. In a general way, the topographic characters of this border portion of the Coastal Plain are similar to those described in the Atlantic Border district. The Mesozoic outcrops include only Upper Cretaceous formations in the Gulf Plain east of the Mississippi, and Lower and Upper Cretaceous in the area west of the Mississippi; neither Triassic nor Jurassic rocks are known in any part of the Coastal Plains region. The topography in most places may be described as gently rolling. Harder formations, consisting of sandstone and chalky limestone, form escarpments or ridges that follow the strike of the beds. The seaward slope of these ridges is commonly much more gentle than that facing inland, because the strata dip toward the sea. The outcrop belts of different formations are commonly marked

also by noteworthy differences in vegetation. The sandy uplands are thickly covered with trees, whereas the calcareous shaly lowlands are mostly treeless and form the most fertile farm lands.

Great Plains.—Beginning in the south, we may note the presence of Mesozoic beds in a wide area between Austin and San Antonio, Tex., on the east, and the mountains west of Pecos River, on the west. Triassic sandy beds appear in places, but the chief formations are nearly flat-lying Cretaceous limestones and shales. Under the prevailing arid climate the limestones are quite resistant to erosion, forming plateaus that are bordered by escarpments and intersected in places by narrow canyons. Somewhat similar characters mark Mesozoic outcrops in eastern New Mexico, although hard sandstone beds are the chief escarpment makers in this region. Along the Rocky Mountain Front in Colorado and part of Wyoming, Mesozoic beds are steeply upturned, forming hogback ridges and valleys that follow the strike of the beds. Similar conditions are observed on the flanks that border mountain uplifts like the Black Hills and the Bighorn Mountains.

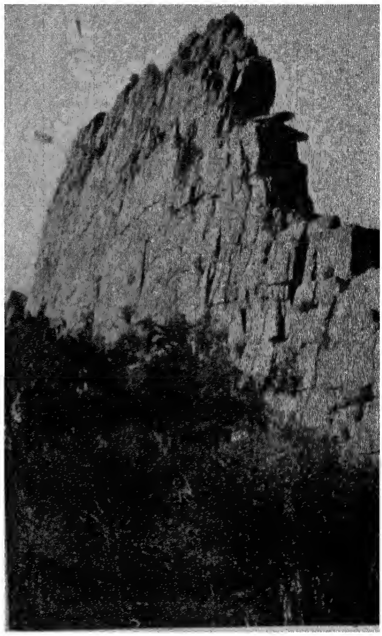


FIG. 236.—Steeply upturned Mesozoic rocks occur on the flanks of the Rocky Mountain Uplift. This view shows a nearly vertical wall of Cretaceous sandstone (Dakota) near Stonewall, Colo. (*N. H. Darton, U. S. Geol. Survey.*)

The Mesozoic formations of the Great Plains, extending from western Kansas northward to the country beyond Alberta, Canada, are nearly flat-lying and the outcrops cover a very large territory. Hard beds, consisting chiefly of sandstones but in the south of limestones also, make hills and escarpments. The shales commonly form gently rolling grassland prairies, but locally they are intricately dissected to form badlands. The dark, somber color tone of the Cretaceous shales in this region is a characteristic feature.

Rocky Mountains.—Mesozoic rocks, consisting mainly of shale and sandstone, are widely distributed in the Rocky Mountains province. The Triassic, Jurassic, and Cretaceous are all represented in most of the Mesozoic outcrop areas. On the flanks of the mountain uplifts and within the mountain districts proper, the Mesozoic rocks are mostly folded and faulted. Because they are much less resistant to erosion than the hard older rocks, they make valleys and so-called "parks." The Wyoming

Basin contains extensive areas of Mesozoic rocks which are flat-lying or only gently folded in most of the basin but near the borders are steeply dipping.

The Colorado Plateau region, including most of southern Utah, northern Arizona, and parts of Colorado and New Mexico, is an extraordinary country of deep-cut canyons and cliff-bordered plateaus and mesas. It is a land of bare rock, for the cover of soil is thin or in many

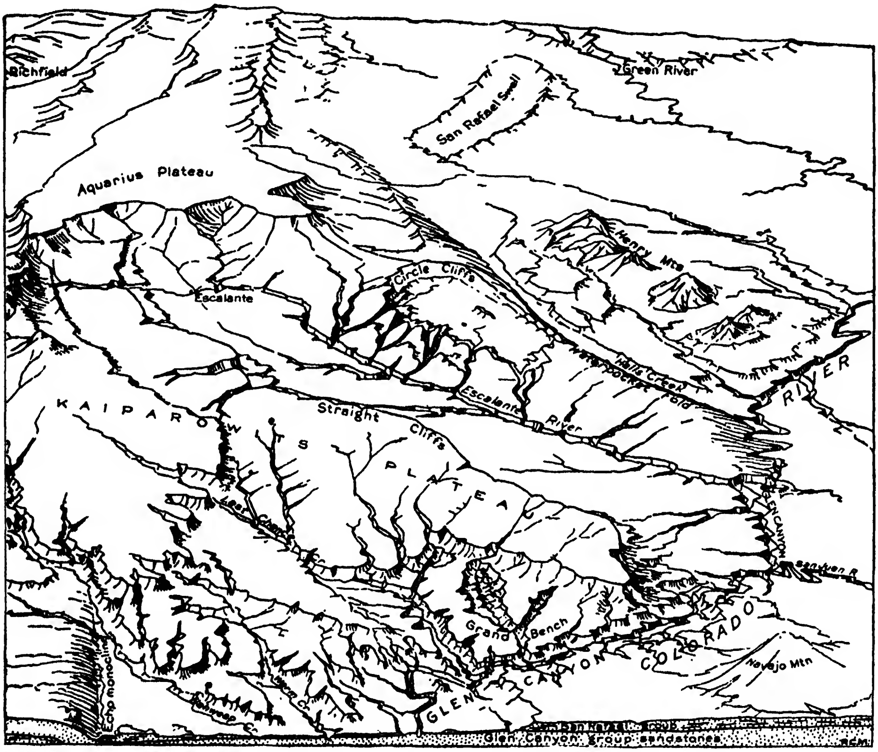


FIG. 237.—Diagram showing plateaus and canyons in a region of Mesozoic rocks in southern Utah. The highest plateau (Aquarius) is capped by Tertiary deposits. (*R. C. Moore, U. S. Geol. Survey.*)

places entirely lacking. Mesozoic formations are widely distributed in this region and they form some of the most imposing features of the rugged landscape. Thick, variously colored sandstones are the dominant hard rock. Red, dark-bluish, and highly variegated shales are the common type of soft beds. The Mesozoic strata are nearly flat-lying, in general, and the hard rocks form a stairlike succession of plateaus, one above another, the highest made by the youngest formations. Along certain lines the rocks are steeply tilted, however, forming monoclines. Here, the hard rocks make prominent hogbacks and the weak strata produce very elongate strike valleys.

Pacific Border.—Sedimentary and igneous rocks of Mesozoic age form much of the mass of the westernmost mountains of the continent, from Alaska to Lower California. The eastern part of this belt comprises the Sierra Nevada Mountains in California, the Cascade Mountains in Oregon and Washington, and other ranges reaching far northward into western Canada. The western portion of the belt forms part of the Coast Ranges.

The Mesozoic sediments are very thick and in most places have been much disturbed by folding and faulting. Limestone and sandstone are prominent in some places and in some parts of the section, but the dominant type of rock is sandy shale. Middle Mesozoic rocks contain great thicknesses of volcanic rocks and sediments derived from volcanics. Large intrusions of granitic rock of Mesozoic age now form some of the prominent mountain heights.

MESOZOIC FORMATIONS OF OTHER CONTINENTS

Europe contains large outcrop areas of Mesozoic rocks. The most important regions are southeastern England, the Paris Basin in northern France, the eastern and southwestern borders of the Central Plateau of France, the Pyrenees and scattered areas in northeastern Spain, the Alps, southwestern Germany, the Carpathian, Balkan, and Caucasus Mountains, and a large area in central and southeastern Russia.

The topographic characters of these regions are controlled mainly by the hardness of the Mesozoic formations and their structure. For example, the highlands of northern England, formed by Upper Paleozoic rocks, are bordered by the Central Plain that is made by the outcrop of weak Triassic beds. On the southeast of this plain is a long belt of Jurassic outcrops, the beds dipping gently southeastward. These rocks are moderately hard and form an escarpment facing the Triassic lowland. Cretaceous beds occupy most of southeastern England, being especially well shown in cliffs along the English Channel. Rolling hills and valleys, well covered with grass but with few trees, distinguish this region.

The structure of northern France is that of a broad, shallow basin. The hard Mesozoic rocks form escarpments which face outward on all sides with gentle dip slopes inclining toward the center of the basin. There are several lines of such escarpments made by successively higher beds of the Mesozoic sequence. It is interesting to note that these escarpments determine the location of the main lines of fortification that have been erected for the defense of Paris, and that these topographic features exerted a major influence on military operations in the World War.

Massive limestones, very steeply folded and overthrust, are prominent in the Alps, Pyrenees, Carpathians, and other mountain chains of southern Europe. Altogether, the rocks of Mesozoic age form a very prominent part of the surface of this continent.

Asia.—The Asiatic continent consists essentially of two very stable blocks of the earth crust, one in the north known as Angaraland and the other in the south represented by India. The latter area is only a remnant of a former extensive continental mass that in Mesozoic and part of Paleozoic time extended southwestward toward Africa. This crustal block is termed Gondwanaland. Between the northern and southern blocks is a geosynclinal belt of thick sediments. This marks the site of a very persistent seaway (called Tethys), for a large part of the rock formations are marine. The region has been subjected to compressive stresses, which have operated to produce the great Himalayan mountain chain.

Mesozoic formations of continental origin are known in much of the Gobi Desert, Mongolia, and Siberia, which form parts of the Angaraland crustal block. Similar beds occur in India, associated with enormous outflows of basaltic lava in the Dekkan Plateau. The Himalayan belt contains thick beds of marine Triassic, Jurassic, and Cretaceous age.

Africa.—During Early Mesozoic time the African continent appears to have stood well above sea level, just as it did throughout most of the Paleozoic era. Very thick continental formations, consisting largely of sandstone, are known in South Africa and in the Congo Basin. These deposits are included in what is known as the Karroo system, of which the basal part is Permian, and the middle and upper parts Triassic

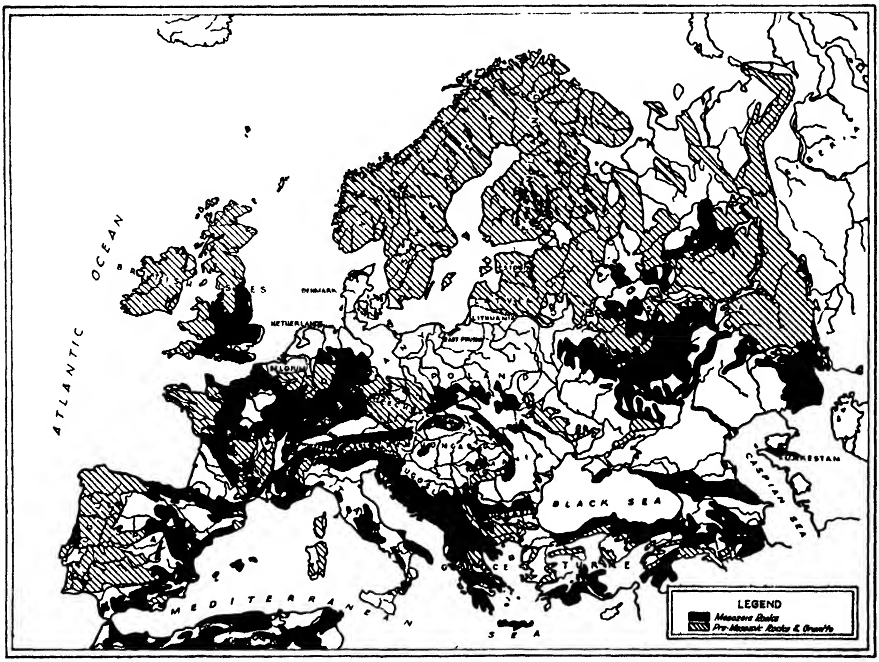


FIG. 238.—Map of Europe showing outcrop areas of Mesozoic rocks.

and Jurassic, respectively. Marine Jurassic is known along the east African coast and in western Madagascar. Cretaceous deposits are developed mainly in North Africa and along the western coast, in part of southeastern Africa, and in western Madagascar.

Australia.—Mesozoic strata cover a large part of eastern Australia and a narrow fringe along the western border. Triassic beds are best known around Sydney, in New South Wales. Coal-bearing continental Jurassic formations occur also in this region, and marine Jurassic near the coast in far western Australia. Much the greatest area of Mesozoic rocks, covering most of Queensland and parts of adjoining provinces, consists of Cretaceous marine strata.

South America contains Mesozoic rocks, the chief outcrop areas being located in the Andean mountain chain. This western border region of the continent was a geosyncline in Mesozoic time. Triassic, Jurassic, and Cretaceous deposits are all present in the geosynclinal belt.

SUMMARY

The Mesozoic formations possess no essential distinctions in lithologic character, excepting possibly a generally less strongly compacted nature than in the case of the Paleozoic rocks. The fossils show easily recognized and important differences, in most cases, from those of older and younger eras.

Outcrops of Triassic rocks near the Atlantic Border of North America, from Nova Scotia to North Carolina, make lowlands that in most cases are nearly or entirely surrounded by older rocks. Cretaceous formations compose the inner border of the Atlantic and Gulf Coastal Plains in most places. The rocks are generally weaker than those of adjoining districts toward the continental interior, and consequently they make a plains country that is somewhat lower than the inland areas. Hard formations form escarpments.

The Great Plains are largely underlaid by Mesozoic rocks, most of which are Cretaceous. Plateaus capped by limestone occur in the south. The largest continuous outcrop areas of Mesozoic rocks on the continent are found in the northern Great Plains, extending from Kansas to northwestern Canada. This is mostly a gently rolling grassland country.

All of the Mesozoic systems are well represented in the Rocky Mountains region. The outcrops bordering the mountain uplifts are narrow because the strata are steeply tilted. The Colorado Plateaus contain extensive areas of Mesozoic beds that are prominent in making the steep-walled canyons and lofty escarpments which characterize this region.

Much of the surface of Europe is formed by outcrops of Mesozoic rocks. The rocks of this age are nearly flat-lying in England, northern France, Germany, and Russia but are strongly folded in the Alps and other mountain chains of southern Europe. The Himalayan geosyncline of Asia contains a thick succession of marine Mesozoic strata, and the relatively stable crustal areas to the north and south contain thick, widespread nonmarine deposits. Mesozoic formations are well developed in eastern Australia, northern Africa, and western South America.

CHAPTER XXII

FORMATIONS AND PHYSICAL HISTORY OF TRIASSIC TIME

The Triassic period, which comprises the first chapter of Mesozoic earth history, was a time of general continental emergence, marked by erosion of the lands and in places by thick nonmarine sedimentary deposits. Fossils of the land deposits show the beginnings of many strange vertebrates and a distinctive assemblage of plants. Shallow seas advanced on parts of the lands, leaving record of a host of interesting marine organisms.

In North America the Triassic formations are dominantly of subaerial origin, deposits of this sort being found along the Eastern Border and over much of the Western Interior region, but adjacent to the Pacific there are thick marine beds. The portions of the continent in which no rocks of this age are known greatly exceed the area containing Triassic rocks. Most of the territory that lacks Early Mesozoic deposits was then presumably subject to erosion.

Definition and General Character.—There is an unconformity at the base of the Triassic system in practically all known sections. This fact, together with the important change in characters of the marine life, makes definite the line of division between Triassic and Permian. An exception apparently exists in the case of some regions of continental sedimentation where accumulation of mostly unfossiliferous red sands and clays, which began in the Permian period, continued with little, if any, interruption into Early Mesozoic time. Also, there are some places where lack of evidence as to age from either fossils or stratigraphic relations leaves uncertainty as to whether a formation is really of Permian or Triassic age. Both of these conditions are found in the nonmarine deposits of the Western Interior of North America and also in South Africa where Late Paleozoic and Early Mesozoic continental beds occur together. Yet, on the whole, the sharp demarcation of the Triassic rocks from older strata is a noteworthy point. This break corresponds in time to the retreat of the seas, and the mountain-building on land that terminated the preceding period and era.

The top of the Triassic, as defined in the type region of Germany, is marked by cessation of continental deposition and beginning of marine sedimentation that is classed as Jurassic. Also, there is a very great change from the faunas of the marine Upper Triassic rocks to those of the Lower Jurassic formations, as indicated by voluminous paleontologic

evidence in the rocks of south central Europe. The Early Mesozoic marine beds in America are identified chiefly by comparison of their fossils with European and Asiatic faunas. Nonmarine deposits of the Western Interior are less definitely placed, the boundary at the top of the Triassic system being at present unsettled.

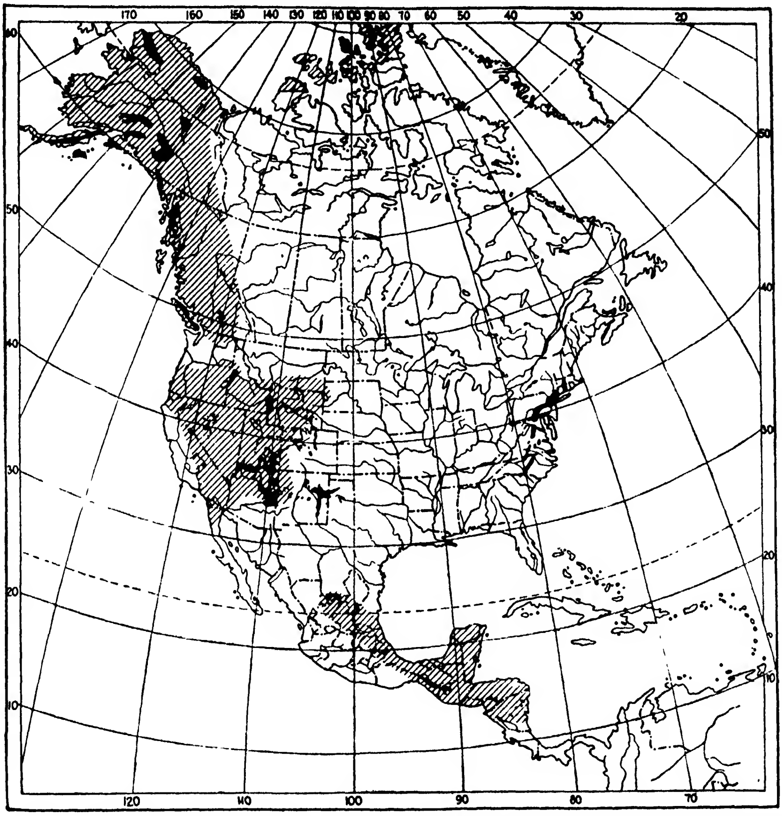


Fig. 239.—Map of North America showing outcrop areas of the Triassic system (black) and the inferred area of original distribution of Triassic formations (oblique shading). (*V. R. D. Kirkham, in Chamberlin and Salisbury's Historical Geology, Henry Holt & Company.*)

The Triassic formations of North America are conveniently and naturally grouped according to geographic distribution and general lithologic characters in three regions: the Atlantic Border, Western Interior, and Pacific Border. The last two of these are partly joined together, for in Early Triassic time the Pacific sea extended to Utah and Wyoming.

Outstanding characters of the Triassic rocks in eastern North America are their (1) occurrence in narrow, elongate deep troughs, (2) great thickness, (3) tilted and faulted but generally unfolded structure, (4) continental origin, and (5) association with dark-colored intrusive and

extrusive igneous rocks. The Western Interior region contains non-marine and marine deposits, mostly red and variegated, vividly colored sandy silts and clays that cover a very large territory but are not nearly so thick as the eastern Triassic beds. On the Pacific Border, especially in eastern California and Nevada, are thick dark-colored marine shale, limestone, and sandstone, in which some formations are abundantly fossiliferous. The strata in this region have mostly a very complex structure, and associated volcanic rocks are common.

TRIASSIC FORMATIONS OF NORTH AMERICA

Atlantic Border Region

Distribution.—Triassic rocks occur adjacent to the Atlantic Border of North America in disconnected patches extending from Nova Scotia

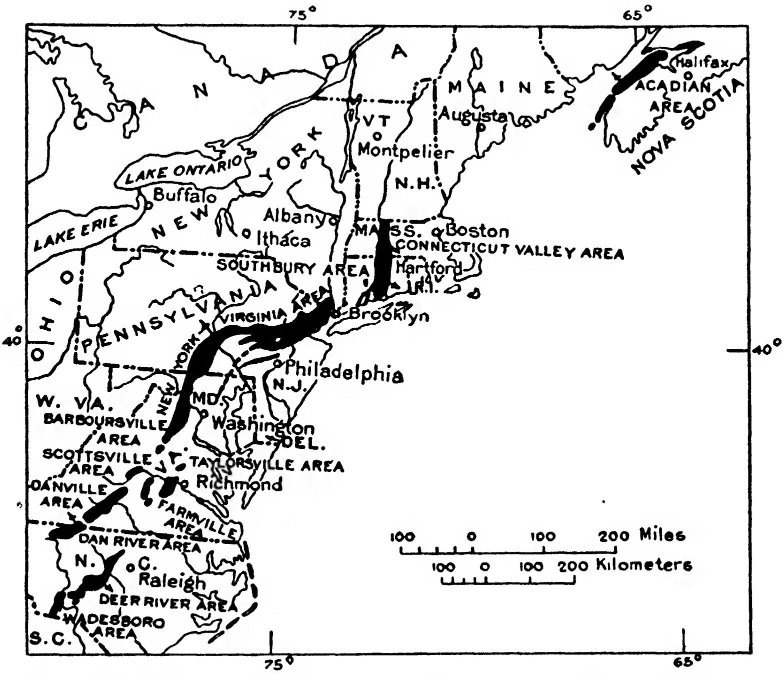


FIG. 240.—Map showing distribution of Triassic outcrop areas in the Atlantic Border region. (*From International Geol. Congress Guidebook 1. Reprinted by permission from Forest Physiography by Isaiah Bowman, published by John Wiley & Sons, Inc.*)

on the northeast to North Carolina on the southwest. The longer axis of the individual outcrops and of the belt as a whole is approximately but not exactly parallel to the trend of the Appalachian Mountains and it roughly corresponds in direction with the present coast line. The Nova Scotian area lies southeast of the Bay of Fundy, parts of the Triassic being covered by waters of the bay and of the Gulf of Maine. The

Connecticut Valley, in western Massachusetts and central Connecticut, is a lowland composed of Triassic rocks. The trend of the valley and strike of the rocks are nearly north-south, and the dip of the rocks is eastward. Extending from the west bank of Hudson River opposite New York City, a third Triassic belt trends southwestward across northern New Jersey, southeastern Pennsylvania, and north central Maryland into Virginia (see Fig. 240). This is a lowland in which the rocks dip northwestward. There are several smaller Triassic areas in Virginia and North Carolina. It is possible that Triassic deposits occur southwest of the North Carolina areas, but, if they do, they are concealed by younger formations of the Coastal Plain.

Lithologic Character.—The rocks of all these Triassic areas are similar in character and are designated as the Newark series, from exposures near Newark, N. J. The deposits are prevailingly reddish-

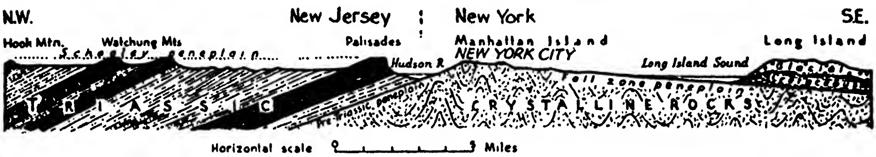


FIG. 241.—Geologic section of Manhattan Island (New York City) and adjacent country showing relation of Triassic rocks in New Jersey to pre-Cambrian crystalline rocks of Manhattan Island. Trap-rock sills (shaded dark) make ridges. Note the west-tilted pre-Triassic peneplain, the east-tilted pre-Cretaceous Fall Zone peneplain, and the nearly horizontal Schooley peneplain. (*D. W. Johnson, U. S. Geol. Survey.*)

brown in color and consist mainly of sandy shale and sandstone. Some of the sandstones are thick and show prominent cross-bedding. Others are thin and interbedded with shale. Feldspar is a prominent constituent, indicating dominance of mechanical over chemical weathering in the areas that supplied the sediments. Bedding is generally irregular and the sorting of grains in the rock is poor. Locally, especially toward the margins of the basins that contain these deposits, there are conglomerates. The name "fanglomerate" has been applied to some of these accumulations of gravel and cobbles because the deposits are fan-shaped and were evidently deposited as coarse alluvial fans by streams that dumped their load of gravelly wash into the basin exactly as streams build similar fans in intermontane valleys of the western United States today. Some beds are more regular, suggesting deposition on flood plains or in shallow temporary lakes (playas). Clearly marked footprints of land reptiles, and mud cracks, raindrop impressions, and other marks of continental deposition occur. The only fossils are those of land plants, fresh-water fishes, a few invertebrates, and land reptiles.

The Virginia and North Carolina Triassic deposits contain black shale and coal beds along with the red sandy beds. The carbonaceous

deposits indicate existence of lakes and swamps in or adjacent to which there was an abundance of plants.

Source of Sediments.—The source of most of the materials in the Newark series is believed to be somewhat distant, that is, not immediately adjacent to the present basins. Reasons for this conclusion are the prevailing fineness, uniformity, and red color of the sediments, and lack of resemblance to old rocks at the margins of the basins. Most of the sand and silt was probably carried 20 to 200 miles before it came to rest as part of the Triassic deposits in this region. On the other hand, there are materials that are clearly of very local origin. These include pebbles and cobbles of limestone that could not have been carried far.

Igneous Rocks.—A characteristic feature of the eastern Triassic strata is the occurrence of dark-colored igneous rock (basalt, diabase) which is commonly called *trap*. It is chiefly found in the form of sheets parallel to the sedimentary rock layers, but there are also dikes. Extrusions or fissure eruptions of the quiet type are seen, in which lava flowed out upon the sediments, in some cases spreading long distances. There are also intrusions in which the molten material forced its way laterally between layers of the stratified rocks. Some of these intrusive sills are surprisingly extensive. The dikes, consisting in many cases of congealed lava in the fissures that supplied the flows or sills, intersect the bedding of the stratified rocks roughly at right angles. Some of them are traced for many miles beyond the present Triassic sedimentary outcrops into areas of older formations.

The trap rocks are hard. They are so much more resistant than the sedimentary rocks that they are very prominent topographically, forming long hogback ridges and in places making conspicuous cliffs, like the Palisades of the Hudson near New York City or West Rock at New Haven.

Structure.—The rocks of the Newark series are rather uniformly inclined at angles ranging from 10 to 25 degrees, this dip being evidently the result of post-Triassic tilting. Most of the beds had some initial slope in the direction away from their source, for they are alluvial fan deposits mainly. The direction of dip that is observed in different basins differs, but it is approximately the same in each basin. The Nova Scotian Triassic rocks dip northwestward, those in the Connecticut Valley eastward, in the New Jersey-Virginia area northwestward, and so on. The distribution of these oppositely directed dips affords some basis for the conclusion that the existent Triassic belts are the remnant limbs of a former broad anticlinal arch, faulted at the margins and eroded in the middle (Fig. 242).

Another structural feature of much importance is normal faulting. The margins of the basins on one or both sides are found to follow fault lines, along many of which there has evidently been great vertical move-

ment, the sediment-filled basin being downthrown while the bordering older rock is upthrown. Some of these faults may have originated during the time of Triassic sedimentation, sinking of the basin taking place progressively or recurrently as the load of stream-borne waste accumulated. Others are probably related to the crustal movements that elevated and tilted the Triassic rocks later on. Within the basins are also many normal faults, which, however, do not generally have a large throw. They slice the rocks into minor blocks of varying dimensions and shape, offsetting and not infrequently duplicating outcrops of beds. This effect on outcrops is prominent in places where resistant layers like the trap sheets occur, but in soft rocks, which are mainly soil-covered, surface indications of faulting are difficult or impossible to observe.

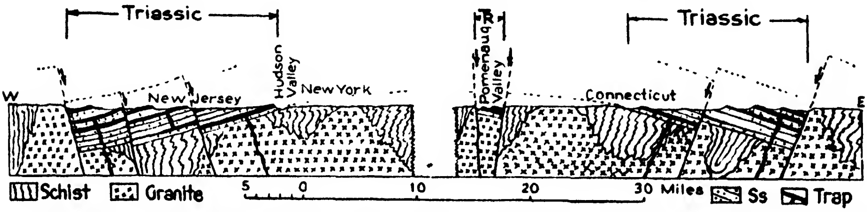


FIG. 242.—Section of the New Jersey and Connecticut Triassic belts showing opposite dips which suggest possible anticlinal structure of an originally connected series of Triassic beds. (*C. R. Longwell, U. S. Geol. Survey.*)

It is certain that very many faults in the weak-rock portions of the Triassic are unknown and unmapped.

Thickness.—The Newark series is very thick, but the exact amount of the thickness in different basins is uncertain. In the first place, the initial angle of bedding, including variations in this angle in different parts of the basin due to the nature of fluviatile deposition, and also due to differential subsidence during sedimentation, must be considered in computing actual thickness. In the second, the prevalence of faulting, and especially the presence of undetected faults, interferes with measurement and may lead to errors. Certainly the thickness of Triassic rocks now remaining is less than the original thickness, for only the parts of the down-faulted blocks below the level of comparatively recent peneplanation are still present. The Connecticut Valley Triassic deposits are reported to be 10,700 to 13,000 feet thick, of which about 800 feet consists of trap sheets. The New Jersey and Pennsylvanian Triassic rocks are said to have a thickness of about 20,000 feet in some places.

Age and Comparison.—The age of the Newark beds is Late Triassic, as indicated by their fossils. Since these rocks lie directly, and, of course, unconformably, on Paleozoic or older rocks, no deposits of Medial or Early Triassic age are known in the east. The beds found next above the Newark belong to the Lower Cretaceous.

In several features, notably general lithology of the sedimentary rocks, thickness, structure, and dark-colored sills and flows of igneous

rocks, the Newark series strikingly calls to mind the Proterozoic rocks of the Grand Canyon region in Arizona. Most significant, seemingly, is the association in both cases of geographically extensive trap rock with the deep subsidence and down-faulting of the sediment-filled troughs. The sinking appears to be genetically linked to the igneous activity.

Western Interior Region

General Character and Distribution.—Chief characters of the Western Interior Triassic deposits are their vivid colors, dominantly continental origin, widespread distribution, and relative thinness as compared with Newark beds. Also, part of the western Triassic beds belongs to the early portion of the period. The rocks are mostly sandy shale and thin sandstone beds, but there are some conglomerate, gypsum, and a little limestone. Typical outcrops are found in the Painted Desert of northeastern Arizona, the Chocolate and Vermilion Cliffs of southern Utah, and in red-rock valleys and semidesert areas of New Mexico, Colorado, and Wyoming. The easternmost exposures are found in the Black Hills of South Dakota and in northwestern Texas. The Triassic probably underlies parts of western Nebraska, Kansas, and Oklahoma, where it has been identified tentatively in wells and at outcrops in southwestern Kansas and northwestern Oklahoma. Resemblance of these rocks to red beds of Permian age makes determination difficult without assistance of fossil evidence. Southward and northward the Triassic formations of this region fail to reach the Mexican and Canadian boundaries, but westward there is connection with the Pacific region, a boundary here being rather arbitrarily drawn on the basis of present geographic separation of outcrops and differences in the deposits.

The Arizona-Utah Section.—An area as great as that of the Western Interior region naturally shows considerable variation in the character and thickness of the Triassic formations. Yet, in a general way, there are similarities. We may base our study of the Western Interior Triassic deposits mainly on the portion of them that occurs in northern Arizona and adjacent states, for this section is typical, very well exposed, and carefully studied.

The Triassic is distinguished from the Permian in parts of this region by marked difference in lithologic characters but in other parts the beds are very similar. A clearly defined unconformity is commonly found at the base of the Triassic beds, for a coarse conglomerate rests on an uneven, stream-carved surface of marine Permian rocks. Even where rocks of the two systems show lithologic resemblance, the boundary is definitely located in most places by difference in structure, presence of an unconformity, and minor lithologic features.

The oldest Triassic formation of the Arizona-Utah country consists of chocolate- or reddish-brown sandy shale and sandstone (Moenkopi),

fairly uniform in bedding. The prevalence of thin, even bedding furnishes basis for the conclusion that the formation is mostly a deposit made in a large water body. Some of the platy sandstone layers are beautifully ripple-marked, and the thicker beds commonly show cross-bedding which indicates current action. Gypsum is found in scattered crystals and irregular veins, while toward the west there are prominent gypsum beds and also marine fossil-bearing limestone. The thickness of the formation, about 500 feet in this region, decreases eastward but

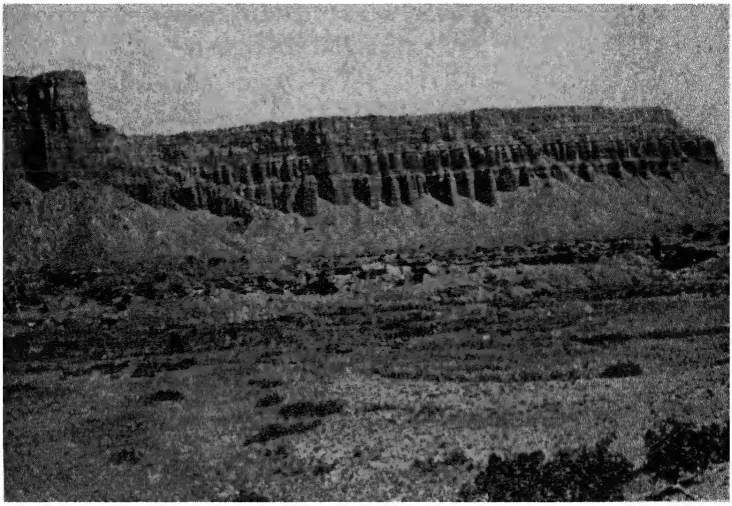


Fig. 243.—The Chocolate Cliffs in southern Utah near Kanab. The thinly and evenly bedded rock is the Lower Triassic Moenkopi formation. The cap rock is Shinarump conglomerate. (*J. K. Hillers, U. S. Geol. Survey.*)

increases gradually westward to more than 2,000 feet in southern Nevada. The lowest Triassic beds here are evidently of marine and possibly in part lagoonal or deltaic origin.

The next higher formation (Shinarump) is an interesting deposit consisting mostly of gravel and grit, which is now cemented to form a hard rock, capping benches and mesas. It is a stream-laid deposit that rests unconformably on the underlying beds. The original area over which this deposit was spread is not less than 75,000 square miles, but the average thickness of the formation is only 50 feet and the maximum about 200 feet. This is indeed a remarkably thin and extensive veneer of fluviatile debris. Petrified logs are found in many places and fragments of petrified wood are so common that they are characteristic of the formation. The unconformity at the base of the Shinarump beds is shown by valleys carved in the underlying strata and filled by sand and gravel of this formation, and also in places by slight differences in the dip of the higher and lower beds. Fossils indicate that the Shinarump

belongs to the Upper Triassic series, the unconformity thus marking erosion that took place in Medial Triassic time. Beds of Medial Triassic age are known elsewhere in the west but are absent here. The original thickness of Lower Triassic deposits has been reduced an unknown amount by the pre-Shinarump erosion.

The upper part of the Triassic system in the Arizona-Utah region is a highly variegated, vividly colored formation (Chinle) composed of clay, sandy silt, sand, and impure limestone, all of fresh-water origin. The calcareous beds are composed of irregularly shaped nodules and pellets of limestone embedded in a soft matrix; they are very peculiar and are characteristic of this part of the Triassic section. Much of the

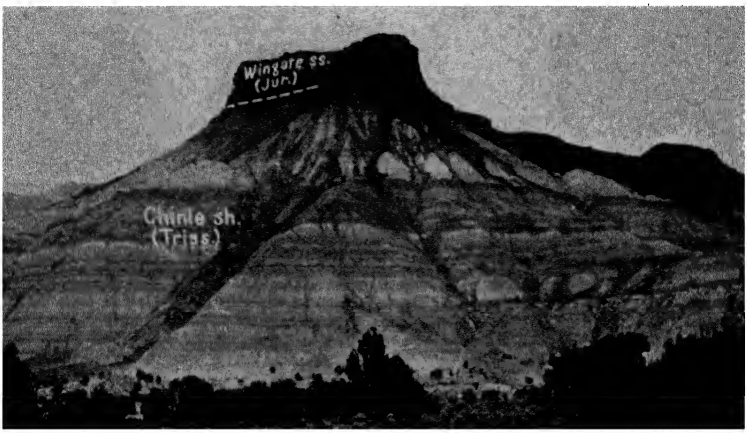


FIG. 244.—Upper Triassic (Chinle) shale, House Rock Valley, southern Utah. (*R. C. Moore, U. S. Geol. Survey.*)

"paint" of the Painted Desert comes from the Upper Triassic rocks, which are soft and mostly bare of soil. The beds are intricately carved in badlands or form naked slopes beneath sandstone cliffs, the successive bands of rose, lavender, maroon, azure, and many other shades making thus a truly striking display of colors. This is the formation that contains the numerous silicified logs of the Petrified Forest National Monument in eastern Arizona and of many other places in the southwest. Some of the logs are 4 feet in diameter and more than 100 feet in length. Bones of land reptiles are also widespread in this part of the western Triassic. There are occasional fairly complete skulls or skeletons, but most common are fragments of bones and teeth of the so-called "saurian conglomerates."

An interesting deposit that is widespread in the Upper Triassic series of the southwest is bentonite. Beds of this clayey material, which is altered volcanic ash, have a thickness up to 8 feet in northern Arizona.

Other Sections.—An interesting, very thick section of Triassic rocks occurs in the Wasatch Mountains of north central Utah. The structure

is very complex, owing to later folding, and the Triassic strata stand vertical or in places are overturned. The Lower Triassic series is very well developed, containing at the base about 1,000 feet of beds that appear to be older than the lowest Lower Triassic of Asia. Middle Triassic marine beds, not known to the south, have been reported (Matthew) here.

Central and northern Utah, Idaho, Colorado, Wyoming, and South Dakota contain Triassic red beds consisting of sandy shale and sandstone. The deposits are many hundreds of feet thick in most places and are chiefly distinguished by their strong red color. Fossils are rare in most places. Even bedding of some of the formations clearly indicates deposition by water, in lakes and as sheet-wash and flood-plains sediments. Gypsum deposits were formed by partial evaporation of salt lakes.

Pacific Region

The westernmost Triassic outcrops of the continent are found in Nevada, California, Washington, western Canada, and Alaska. The formations are dominantly marine and consist largely of dark-colored shale, limestone, and, in places, much sand. Some beds contain very abundant well-preserved fossils that correspond closely with organisms found in the Triassic of Asia and the Mediterranean region of Europe. Lower Triassic marine deposits occur in Idaho (5,300 feet), southeastern California, and southern Nevada. The Idaho Lower Triassic includes about 2,800 feet of limestone. Middle Triassic rocks are best known from southeastern California and Nevada; they consist of 200 to 1,000 feet of shale and shaly limestone.

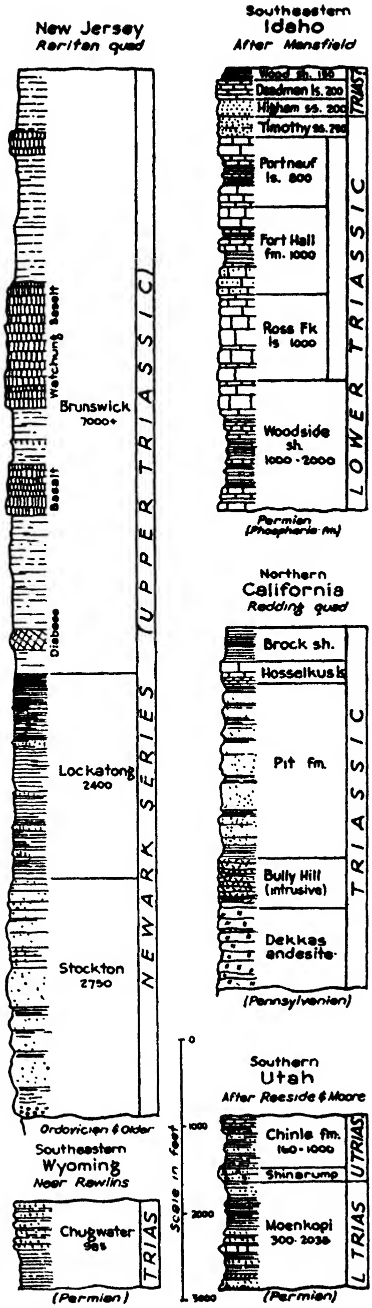


FIG. 245.—Generalized sections of the Triassic system in New Jersey, Idaho, California, and southern Utah.

Upper Triassic marine rocks are well developed in northern California. In central Nevada the Triassic system has a reported total thickness of about 16,000 feet.

Characteristic of much of the West Coast Triassic formations is the very large proportion of volcanic materials that are mingled with the fine sandy and clayey sediments. Parts of central British Columbia and the coastal district, including Vancouver and Queen Charlotte Islands, contain great thicknesses of these argillaceous and volcanic rocks (probably exceeding 15,000 feet in places). Because of later mountain-building, the strata are closely folded, faulted, and locally metamorphosed. There is great variation from place to place, and, because of the complexity of structure and lack of detailed study, much remains to be learned about these beds. Fossils show very close relationship to Asiatic types, and these in turn are in part very much like the species found in the Mediterranean Triassic beds of Europe.

FOREIGN TRIASSIC DEPOSITS

Europe.—In Europe, as in North America, there are widespread nonmarine deposits and thick marine formations. The region in which the continental sediments predominate includes England, eastern France, Germany, western Russia, and Spain. The marine rocks occur chiefly in the Alps district and southeastern Europe, but Middle Triassic beds are extensive in the north central and northern parts of the continent. The Lower Triassic is conspicuous in Svalbard (Spitzbergen).

The type Triassic section is that of Germany, where the three divisions of the system are termed Bunter, Muschelkalk, and Keuper, named in order from oldest to youngest. (1) The *Bunter* consists mainly of yellowish to reddish sandstone in thick and thin beds, some layers being strongly cross-bedded. There are also red and variegated clays, conglomerates, and in the upper part some deposits of salt, gypsum, limestone, and dolomite. The thickness ranges from about 600 to more than 2,000 feet. This part of the Triassic system is thought to represent stream deposits, windblown dune sands, and deposits in lagoons at the sea margin. Some layers show numerous ripple marks and in others mud cracks are common. There are also footprints of land reptiles. Altogether the beds are much like the Triassic deposits of eastern North America or of parts of the Western Interior region. (2) The *Muschelkalk*, about 800 to 1,100 feet in thickness, is marine. The lower and upper divisions consist mostly of limestone, in part sandy or dolomitic. The middle is made up of dolomite, shale, anhydrite, gypsum, and rock salt. The deposits thus indicate a considerable spread of the sea in early mid-Triassic time with normal marine environment, then a time of partial inclosure of the German basin accompanied by desiccation, and in the latter part of the epoch a return to the earlier conditions. Differences in the fossils of the Muschelkalk and those of contemporaneous marine beds of the Alps region imply lack of easy intermigration. (3) The *Keuper* includes red and variously colored shale and sandstone of nonmarine origin, and also in places salt, gypsum, and beds with marine fossils. The thickness ranges from 800 to about 2,000 feet.

The Triassic rocks of England consist almost entirely of continental deposits, mostly reddish sandstone which is called the New Red sandstone, in distinction to the so-called Old Red sandstone, of Devonian age, in Wales and other districts. The Muschelkalk marine phase of the north European Triassic did not extend into England.

The Triassic section of the Alpine and Mediterranean region is very unlike that of Germany, for the system consists mostly of marine beds and contains very thick massive limestone and dolomite. In places there are great bodies of limestone, without bedding, that mark reefs of calcareous algae. The "Dolomites" of the Tyrol are huge crags of this rock which is here 3,000 feet or more in thickness. Fossils are very abundant in some beds.

Other Continents.—Marine Middle and Upper Triassic rocks of the Mediterranean region extend eastward into the Himalayan region of Asia where they attain a considerable thickness. The Lower Triassic beds are less widespread and thinner. Deposits of Triassic age occur also in eastern Siberia and Japan, in the East Indies, Australia, and New Zealand. The Triassic is known in South Africa and is well developed in parts of South America.

PHYSICAL HISTORY OF TRIASSIC TIME

At the beginning of the Triassic period, North America was probably somewhat larger, though not necessarily more rugged and elevated, than now. Nowhere are Late Permian marine deposits known on the continent, and the unconformity at the base of Early Triassic marine rocks in the Pacific Border region shows that this country had previously been subjected to erosion. Except in Mexico, the western part of the United States and Canada, and northwestern Greenland, the sea is not known to have gained control in any part of the continent during the period. Land conditions were strongly dominant.

Erosion of the Land.—The Appalachian region was probably more strongly mountainous than now. At least this is justifiable inference as regards Early Triassic time which was not long after the Permian mountain-building. There are increasingly numerous and definite indications, however, as the geologic history of various recent and ancient mountain ranges is more precisely known, that mountains are short-lived as topographic features unless there are renewed uplifts. Accordingly, it is possible that the Appalachians were already much subdued at the beginning of the Triassic period. Absence of Early and Middle Triassic deposits in the east shows that erosion was at work throughout this territory in these parts of the period, the products of erosion being transported somewhere outside of this region, presumably seaward from the present land.

The great Central Interior and northern portion of the continent was certainly a broad lowland. Areas that were gently upwarped in Late Paleozoic time were doubtless being cut down slowly, but the erosion could not have been very important quantitatively, for the sum of all post-Paleozoic denudation in this region is not great. In the west there were evidently uplands adjacent to the region of extensive fluviatile sedimentation, for a large quantity of fine sand, silt, and clay was derived from erosion of older rocks to form the Triassic formations. The prevailing fineness of the sediments and their general uniformity of character

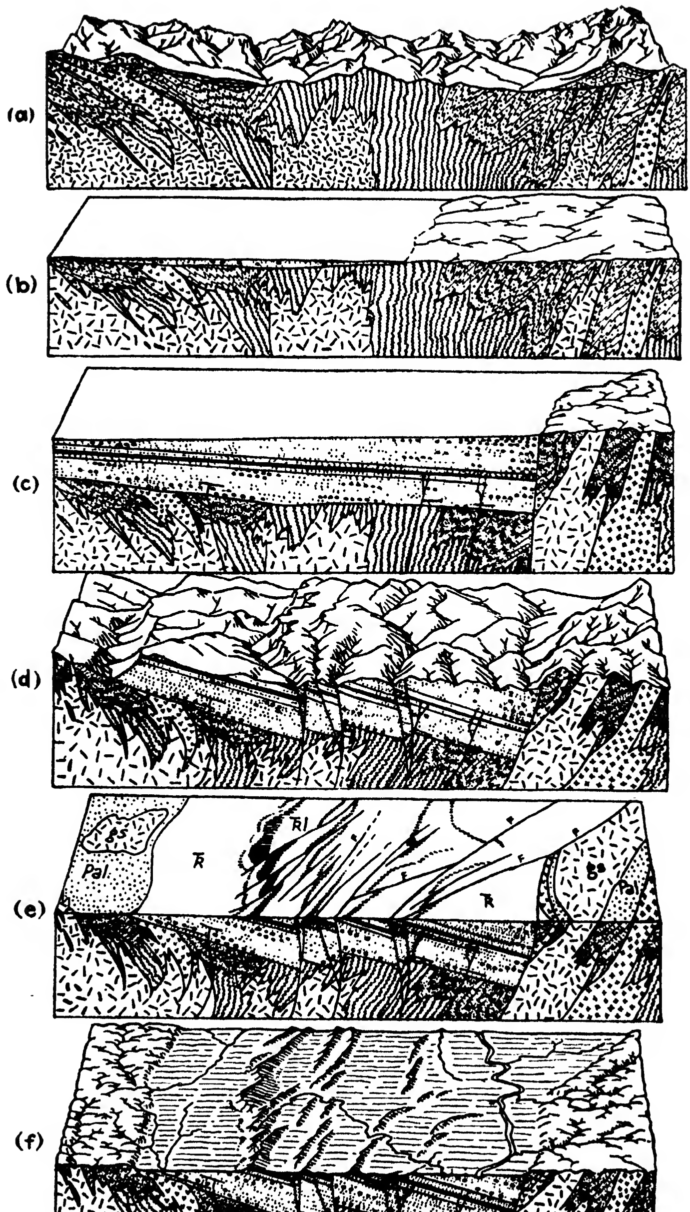


FIG. 246.—Block diagrams representing stages in the geologic history of the Connecticut Valley area between Hartford and New Haven. (*R. C. Moore, from map and sections by Joseph Barrell.*)

a. Mountains forming part of the Appalachian chain, composed of complexly folded and metamorphosed Paleozoic formations and pre-Cambrian rocks.

b. Beginning of Triassic sedimentation. This was preceded by peneplanation of the region, as shown by the smoothness of the surface beneath the Triassic beds.

over great areas do not imply very rapid erosion of mountainous areas close to the sedimentary basins, but rather the contrary.

Sedimentation began in an area adjacent and parallel to the Atlantic Coast in Late Triassic time. Stream-laid gravel, sand, and silty clay were deposited in the form of alluvial fans that gradually filled valley depressions. Lakes and swamps occurred in places. Initiation of this series of deposits may be assigned with little question to a recurrence of the mountain-making crustal movements that formed the Appalachian chain. Uplifted mountain blocks were subjected to active erosion, the products of which were transferred to depressions that gradually sank under the load of accumulating detritus. At certain times there was considerable igneous activity, but eruptions that took place were of the quiet rather than the explosive type.

The western part of the continent was invaded by waters of the Pacific early in Triassic time, greatest thickness of marine deposits being found in the Nevada region. The sea appears to have extended eastward to New Mexico, Colorado, Wyoming, and Idaho, although the shallow-water muds and sands that were deposited in the easterly areas are mostly lacking in marine organisms. Medial Triassic time is represented by marine rocks in eastern California, Nevada, and central Utah (?), but in other places there is an unconformity that represents much or all of this part of the period. In Late Triassic time the sea occupied much the same territory that had been flooded in the preceding epoch and it is known to have extended far to the north in western Canada and Alaska. The Arizona, Utah, Colorado, and Wyoming country was covered by nonmarine clays, silts, sands, and some gravel. Large trees growing on uplands near the region of sedimentation, or possibly in part within it, were carried by streams and buried with the mud and sand. Semiaquatic reptiles are found in places and there are also fresh-water mussels. Considerable volcanic activity along the Pacific Border in Triassic time is shown by igneous rocks and materials that are mingled with the sedimentary formations in a number of places. The occurrence of volcanic ash beds (bentonite) in the Upper Triassic of the Western Interior region proves that there were explosive eruptions of volcanoes in neighboring territory, probably of the Pacific Border, from which the prevailing westerly winds drifted the ash eastward.

Close of the Period.—The Triassic period was brought to a close by geographic changes of some importance, although these are perhaps less

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c. Close of Triassic sedimentation. The deposits and accompanying trap sheets fill a downfaulted trough.

d. Mountains and hills of Early Jurassic time. The Triassic and adjoining older rocks were uplifted (Palisades disturbance) and subjected to active erosion.

e. Peneplanation. The region appears to have been peneplaned in pre-Cretaceous time (Fall Zone peneplain), elevated gently with warping, and peneplaned again in Tertiary time.

f. At the present time the crystalline rocks on the east and west sides of the Triassic belt comprise a dissected upland with even skyline that represents the Tertiary peneplanation. Hogback ridges of Triassic trap rise to the same level, but the weak rocks have been carved to make the broad Connecticut Valley.

noteworthy in North America than elsewhere. There appear to have been relatively sudden and marked changes in the character of the marine organisms, and these changes are presumably due to abrupt and considerable modifications of environment. In North America there were crustal movements along the Atlantic Border which resulted in tilting and faulting of Triassic and older rocks, but there was no appreciable folding. This has been called the *Palisades disturbance* (Schuchert). Mountains were formed, but they were probably not comparable at all with the Late Paleozoic Appalachians.

The western sea retreated for a time at the close of the Triassic period, for there is an unconformity at the base of the oldest marine

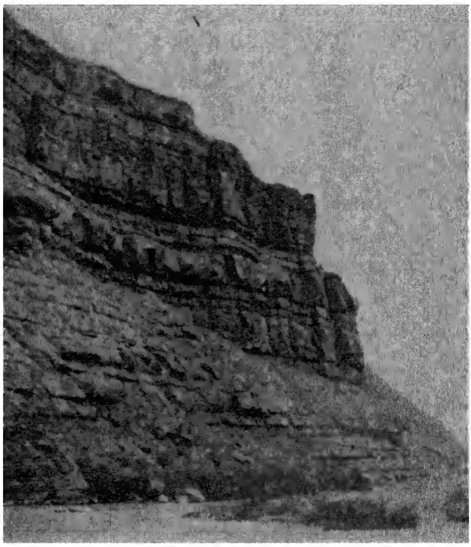

FIG. 247.—Triassic red sandstones (Chugwater) near Tensleep, Wyo. (*N. H. Darton, U. S. Geol. Survey.*)

Jurassic rocks in this region. There is an unconformity also at the base of the great sandstone deposits of the Western Interior which probably marks the line of division between Triassic and Jurassic. At least local upwarping in southwestern Colorado resulted in removal by erosion of 3,000 feet or more Triassic and Paleozoic rocks. Here the Jurassic (Upper) rests unconformably on pre-Cambrian rocks. Folding of Triassic strata is reported in part of Alaska, the deformed and eroded Triassic being unconformably overlaid by Jurassic formations.

Climate.—Prevalence of red beds in areas of Triassic continental sedimentation and common occurrence of gypsum (also salt in Europe) in formations of this age are cited as evidences of aridity. Oxidation of iron that makes the red color may take place under moderately moist

temperate conditions, however, or even in a very moist tropical environment. The weathered detrital materials now being carried from various humid regions of the United States are red in color. The large trees which occur in the "petrified forests" of the western Triassic suggest congenial conditions as regards plant growth, probably plenty of moisture and moderate temperature. The trees have growth rings indicating the presence of seasonal changes, but there is certainly nothing to suggest the stunted growth of desert plants. Similarly, the luxuriant plants of the eastern Triassic coal swamps and lake borders are not arid types, and, even though the red sediments are mostly lacking in organic remains, it may be argued that occurrence of very abundant tracks of reptiles in parts of these deposits is not consonant with the hypothesis of distinct aridity of climate. Conditions in the eastern Triassic basins were probably not very unlike those that prevail in the same region at the present time, or in the central valley of California. The annual rainfall of Triassic time in many places may have been greater than now. Variation in climatic conditions, much as exists today, rather than widespread uniformity may be predicated.

ECONOMIC PRODUCTS

Chief materials of Triassic age that are of commercial value are salt and gypsum. The salt deposits occur in Germany, where they are extensively worked. Gypsum is quarried in Montana, Nevada, Wyoming, and South Dakota, and in places the beds are more than 50 feet thick. Enormous quantities of building stone have been taken from outcrops of eastern Triassic reddish sandstone ("brownstone") of the Newark series, for the rock is easily quarried and fairly strong. Use of this sandstone is much less extensive now, however, than formerly. The hard, tough trap rocks furnish excellent road material and aggregate for concrete work. It is said that the first mined coal in North America was located in the Virginia Triassic area. The coal beds have long been a source of local supply but are of small account as compared with the Pennsylvanian fields.

SUMMARY

The Triassic period comprises the first portion of Mesozoic time. The name is derived from Germany where there are three prominent divisions in the rocks of this age: Bunter (sandstone), Muschelkalk (limestone), and Keuper (red shale and sandstone). The Triassic rocks are mostly well defined stratigraphically, being separated almost everywhere from older rocks by an unconformity and from younger rocks by important differences in fossils and in many places by unconformity. Red beds and other nonmarine deposits are extremely widespread. Marine formations are less extensive than in the later Mesozoic, but they are locally very thick.

North America contains Triassic rocks (1) in a series of elongate narrow troughs trending from northeast to southwest along the Atlantic

Border, (2) in a very large part of the Western Interior, and (3) along the Pacific Border.

The Atlantic areas show only nonmarine strata of Late Triassic age (Newark series). Massive and thin-bedded sandstone, in part strongly cross-bedded, and sandy shale predominate. The color is mostly red or reddish-brown. Locally, there are dark-colored shale and coal beds. The sediments were carried by streams from mountain or upland areas and deposited in valley troughs as great alluvial fans or contributed to shallow lakes. The thickness of these Triassic deposits is great—10,000 to 20,000 feet. Dark-colored igneous rocks (trap) are a striking feature of the Triassic areas. The trap occurs mostly in sheets parallel to the bedding of the sedimentary rocks and represents both extrusive flows and intrusive sills. Because of their resistance to erosion, the trap rocks are topographically prominent at the present time. Post-Triassic faulting and tilting have disturbed the rocks in the various basins, but except very locally the strata are not folded. Subsequent erosion has truncated the inclined beds.

The Triassic of the Western Interior is mainly nonmarine and consists of red beds, varicolored shale, and gypsum. Shale is more important quantitatively than sandstone. Large petrified trees are found in some formations. The western part of the region contains marine deposits as well as fluviatile and some wind-blown materials. In spite of much variation, there are broad similarities in the Triassic formations of widely separated parts of this region. The thickness, about 1,000 to 5,000 feet, is much less than in the east.

The Pacific Border Triassic is largely marine. Some places, as in Nevada, contain beds of Early, Medial, and Late Triassic age, but elsewhere the section is incomplete. Thickness up to 16,000 feet is reported. Volcanic materials are widespread and abundant.

The climate of Triassic time was generally warm and probably humid but locally arid.

CHAPTER XXIII

FORMATIONS AND PHYSICAL HISTORY OF JURASSIC TIME

No geologic period outranks the Jurassic from the standpoint either of the general interest of its record or of the importance of its contribution to geologic science. The marine Jurassic strata of Europe, where first studies of rocks of this age were made, contain a wonderful profusion of well-preserved fossils, and there are distinctions in the shells from different beds or zones that make possible a very detailed and precise, widely applicable subdivision of the system. North America has marine Jurassic deposits in the west, but they are apparently not so fossiliferous, in general, as the European rocks. At any rate, they are still comparatively little known. The American nonmarine Jurassic is of exceptional interest. It offers many intriguing geologic problems, and it presents one of the most imposing displays of varicolored thick sandstones known anywhere.

The Jurassic has furnished to geology the substance on which the foundation of stratigraphy and later much of its superstructure are built, for Jurassic rocks and fossils were the bases of researches that led to development of many important principles of stratigraphic correlation and interpretation. Also, the Jurassic of Europe has been the training ground of many leading geologists and paleontologists—William Smith, Brongniart, d'Orbigny, von Buch, Quenstedt, Oppel, Buckman, and others.

Definition and General Character.—The name Jurassic is derived from the Jura Mountains of eastern France, southern Germany, and northern Switzerland, where there are good exposures of shale, sandstone, and limestone beds with fairly regular character and sequence. Because of distinctive color and other lithologic features, and the presence of many sorts of fossils that differ from organisms in older or younger strata, the Jurassic rocks are easily separated in most places from the Triassic below and the Cretaceous above. Interruptions of sedimentation marked by unconformities define the system also. There are three main divisions of the Jurassic rocks of northern continental Europe: (1) a lower part consisting largely of dark-colored shaly beds, called Lias or Black Jura, (2) a middle part containing prominent iron-rich brown sandstone and oolitic limestone, called Dogger or Brown Jura, and (3) an upper part composed chiefly of light-colored limestone, called Malm or White Jura. The upper rocks are thick, hard, and massive and therefore form prominent

escarpments and ridges. The total thickness of the Jurassic formations in the Jura Mountains region ranges from a little over 1,000 to about 1,800 feet. The deposits here are almost entirely marine, but elsewhere there are some nonmarine beds.

The Jurassic system in western North America includes marine shale, limestone, and sandstone, and also very widespread continental deposits consisting mostly of sand. Along the Pacific Coast, volcanic rocks attain a considerable thickness. Well-defined unconformities are recognized at the top and bottom in many places, but there is uncertainty in the case of some of the unfossiliferous continental formations as to which of two or more unconformities near the base and top of the system precisely define its limits.

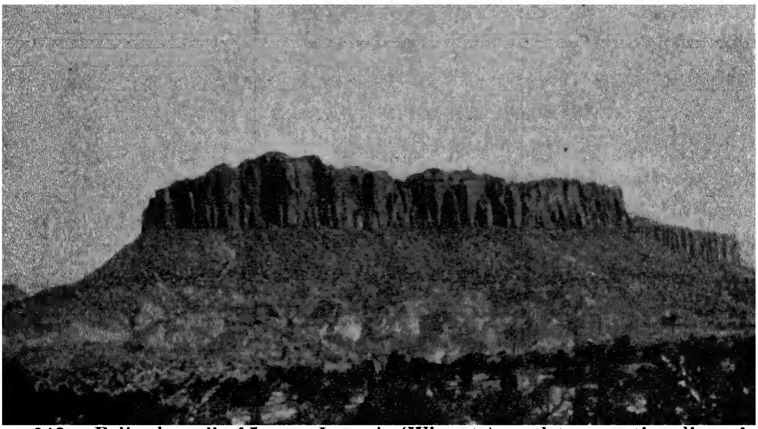

FIG. 248.—Palisade wall of Lower Jurassic (Wingate) sandstone resting disconformably on Upper Triassic (Chinle) shale. Circle Cliffs, southern Utah. (*R. C. Moore. U. S. Geol. Survey.*)

JURASSIC FORMATIONS OF NORTH AMERICA

Outcrops of Jurassic rocks in North America are confined to the western and southern parts of the continent. Study of the general nature of the formations may be divided conveniently into sections devoted respectively to (1) the Western Interior region in which nonmarine sediments are most prominent, (2) the Pacific Border, and (3) Mexican regions in which marine strata predominate.

Western Interior Region

Distribution.—The Western Interior region includes territory in eastern British Columbia, Alberta, Montana, Idaho, Wyoming, western South Dakota, Colorado, New Mexico, Utah, Arizona, and southern Nevada. The distribution of Jurassic rocks is really very extensive. The area in which formations of this age are concealed by younger rocks

is much greater, however, than that in which they now appear at the surface, and there are undoubtedly many thousands of square miles where Jurassic rocks were once present but have subsequently been eroded. On the flanks of the Black Hills, Rocky Mountains, Bighorns, Uintas, and other ranges the outcrops of the Jurassic formations are narrow bands, for the dip is fairly steep. Only in the Colorado Plateau

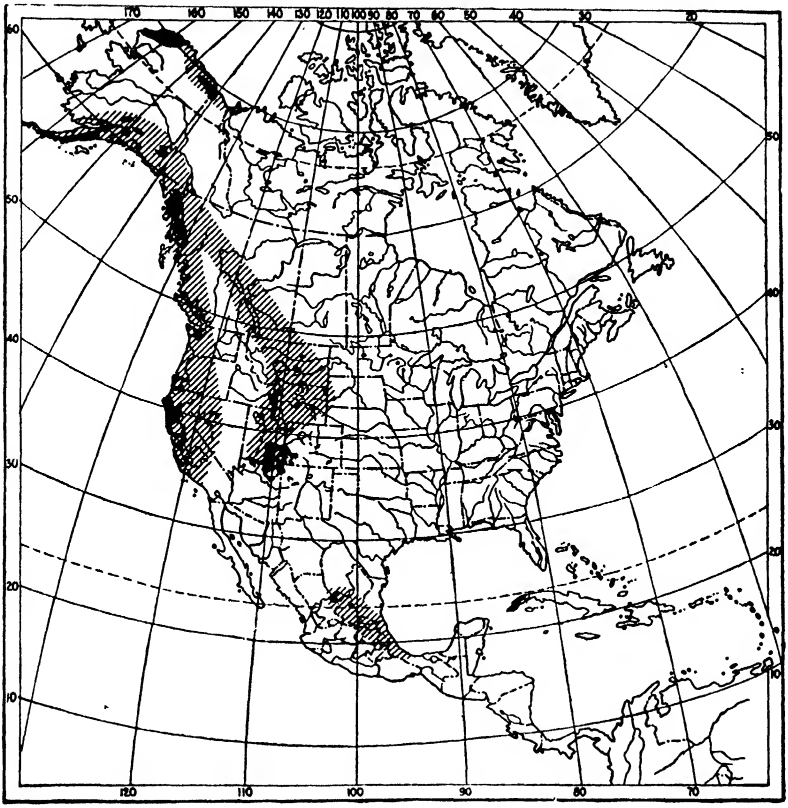

Fig. 249.—Map of North America showing outcrop areas of the Jurassic system (black) and the inferred area of original distribution of Jurassic deposits (oblique shading). (*V. R. D. Kirkham, in Chamberlin and Salisbury's Historical Geology, Henry Holt & Company.*)

country of southern Utah and northern Arizona are there broad areas of Jurassic outcrop. Because this last district is fairly typical of the whole region and because the rocks are strikingly displayed in imposing cliffs and canyons, we may select it for special notice.

Jurassic Section of the Colorado Plateaus.—Traveling northward from the Grand Canyon, one passes from the hard Upper Paleozoic limestone that upholds the plateau near the canyon to lowlands formed by weak Triassic rocks and soon encounters a great impassable wall of sandstone that is made by the lower part of the rock strata classified as

Jurassic. The line of cliffs, a thousand feet or more in height, may be followed for scores of miles, an unscalable obstacle to travel which can be crossed only at a few places where streams have carved canyon valleys. The sandstone (Wingate) is reddish-brown in color, but in the light of the early morning or evening sun it takes on a more brilliant hue that suggested to explorers the name Vermilion Cliffs. A dip slope at the top of the sandstone is inclined gently northward reaching to the base of another great cliff of massive light-creamy tan or white sandstone (Navajo) known as the White Cliffs. This rock is surprisingly uniform in character from top to bottom, practically without bedding except cross-lamination which is developed on a huge scale and shown promi-

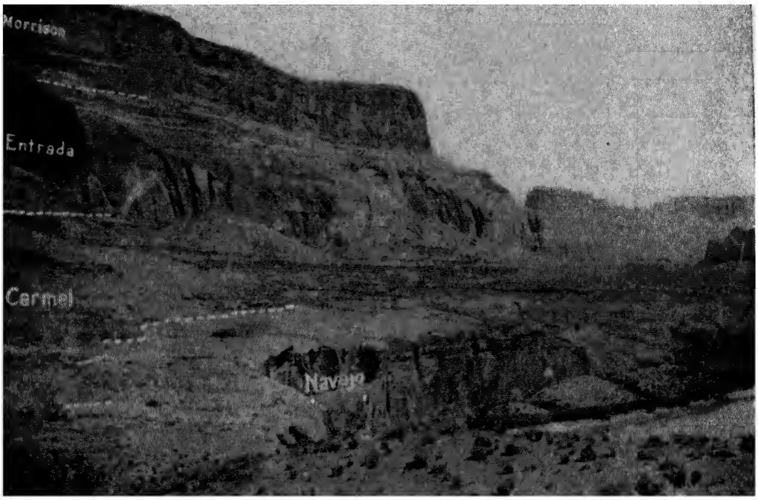

Fig. 250.—Upper Jurassic sandstones (Entrada, Morrison) and marine shale (Carmel) overlying Lower Jurassic sandstone (Navajo). Glen Canyon of Colorado River, southeastern Utah. (*R. C. Moore, U. S. Geol. Survey.*)

nently on weathered surfaces. The formation is more than 1,000 feet thick in southeastern Utah and increases westward to about 3,500 feet in southern Nevada, beyond which point it is not known. Some of the canyons that have been carved in this sandstone are amazingly steep-sided and narrow, many hundreds of feet deep, and not very much wider at the top than at the bottom. Zion Canyon, one of the national parks that is visited annually by thousands of vacation travelers, is eroded in these Jurassic sandstones; and Rainbow Natural Bridge, one of the largest and most graceful features of this sort known, is composed of this rock. The thick sandstones that make the Vermilion and White Cliffs are called the Glen Canyon group.

The higher Jurassic strata (San Rafael group) in the southern Utah plateau country consist of other thick, cliff-forming sandstone formations,

dark-red shale, siliceous limestone, and gypsum. There are at least two horizons in which marine fossils occur and these are traceable for very long distances. It is therefore apparent that the sea covered this part of the Western Interior during some of Jurassic time. Whether the thick cross-bedded sandstones are also marine or nonmarine deposits is not altogether certain, although weight of evidence indicates that they are wind-blown desert sands. Wind-faceted pebbles (dreikanter) have been observed in the sandstone, but fossils are lacking.

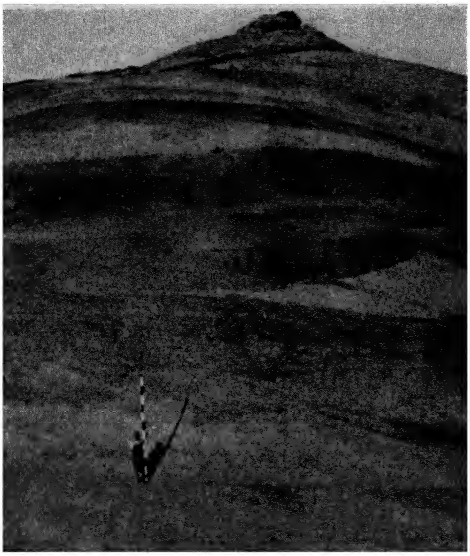

FIG. 251.—Cross-bedding in Lower Jurassic (Navajo) sandstone. This type of bedding strongly suggests wind action. Note the peculiar distribution of red-brown color which appears dark in the view. Circle Cliffs, southern Utah. (*R. C. Moore, U. S. Geol. Survey.*)

Above the marine Jurassic rocks, and separated from them by an unconformity, is a distinctive nonmarine formation (Morrison) that is very widely distributed in the west. It consists of irregularly bedded sandstone, conglomerate, shale, and locally fresh-water limestone of peculiar character; reddish and greenish colors prevail but other tints are common. The deposits are mostly of fluviatile origin. Remains of land animals and land plants are found, but there is question whether they should be classified as Late Jurassic or Early Cretaceous. Recent studies (Reeside) strengthen the conclusion that they should be assigned to the Jurassic.

Taken together, the Jurassic formations of the southwest are the most striking rocks of the plateau country. Certainly they are strongly differentiated in lithologic character from the weak shaly strata of the Triassic below and from the dark shale and entirely different-looking brownish sandstone beds of the Cretaceous above. Thick, cross-bedded

sandstone is the dominant kind of Jurassic rock. The total quantity of sand is so enormous that it taxes imagination. A conservative estimate of the volume of Jurassic sand originally present in the Western Interior states exceeds 50,000 cubic miles of quartz sand. The fact that thickness gradually increases from east to west and the observation that the prevailing inclination of cross-bedding is easterly support the conclusion that most of the sand came from land to the west. If the source of the sand were chiefly granite or other quartz-bearing igneous rock, the disintegration of such material would have yielded far more non-quartzose sediment than quartz grains. Since quartz sand composes so large a part of all the known Jurassic in the Western Interior, it is likely that the source of the quartz was mainly older sandstones and quartzites. It may be noted that thick Paleozoic and pre-Cambrian formations of this sort are known in the region from which the Jurassic sediments are inferred to have been chiefly derived.

The Jurassic rocks in western Colorado are much thinner than in the plateau country farther west. Evidence that the Colorado region was relatively higher than adjoining districts at this time is found in this thinning of the Jurassic deposits, and in the unconformable contact of Jurassic beds on rocks as old as pre-Cambrian. Good exposures of the unconformity at the base of the Jurassic are seen in southwestern Colorado (Piedra River), where Glen Canyon sandstone rests on uplifted and beveled Triassic, Paleozoic, and Proterozoic rocks, and in central Colorado, where the Morrison formation lies on pre-Cambrian granite.

Marine Invasion.—The marine Jurassic rocks of the Western Interior region occur far to the north and are recognized as far east as the Black Hills of South Dakota (Sundance formation). The waters in which these beds were deposited spread southward from an embayment of the Arctic and North Pacific in western Canada, and the fossils show that this sea was part of the so-called Boreal province of Jurassic time, which is well represented in Greenland, England, and Russia. The distribution of the deposits marking various extensions of this sea suggests that the marine invasions were probably separated by withdrawals of major order. Southeastern Idaho contains a thickness of about 6,000 feet of Jurassic strata in which there is record of at least two separate advances of the sea. There is no evidence of a direct communication between the California marine embayment and that which covered Utah and adjacent country to the north.

Pacific Border Region

Jurassic formations occur in much of California, Nevada, Oregon, Washington, British Columbia, and Alaska. Locally, as in western British Columbia, the total thickness is 18,000 feet. Sandstone and dark slaty material predominate but there are widespread limestones and

in places conglomerate is prominent. The Middle Jurassic rocks of California, western Canada, and southeastern Alaska show a large proportion of admixed volcanic (tuffaceous) material which proves that eruptions of the explosive type occurred with frequency in country adjoining this region. As a result of much folding, faulting, and in places metamorphism, which the Jurassic rocks of this region have suffered, their structure is now very complex.

The lower part of the Jurassic (Lias) is identified in southern and western Nevada, northern California, Oregon, British Columbia, and Alaska. Some of the beds contain very numerous fossils. The generally fine-grained texture, large calcareous content, and even, persistent bedding of the Lower Jurassic rocks in the Pacific Border region indicate absence of elevated near-by lands. Excepting a place or two where a small amount of conglomerate is found, even the basal beds are no coarser than fine sandstone.

Middle Jurassic rocks are distributed from California to Alaska but are mostly restricted to a coastal belt that is a few hundred miles wide at the most. Volcanic rocks, consisting of agglomerate, tuff, and lava, are prominent, and in places they have an aggregate thickness of several thousands of feet. There are also extensive marine Jurassic beds that yield abundant fossils. The sequence of volcanic rocks and marine beds shows that eruptions were confined mainly to the early and late parts of Medial Jurassic time, the sea being most extensive and vulcanism least active in the mid-portion of this epoch.

Upper Jurassic marine deposits are widespread in the Pacific Border region. They consist mostly of dark shales. Fossils are abundant in some beds. Volcanic activity of Late Jurassic date is shown by the occurrence of 1,800 feet of tuff in British Columbia associated with Upper Jurassic fossil-bearing beds. There are also volcanic materials of this age in California.

Evidence of early Late Jurassic crustal deformation is seen in southwestern British Columbia (Harrison Lake), where an angular unconformity and thick beds of conglomerate occur, and there are similar but less definite evidences in Alaska and the California Coast Ranges (Crickmay).

Jurassic rocks are absent throughout a belt that extends southward from the Gold Ranges of British Columbia, through Idaho, western Utah, and Nevada, to Arizona and Sonora. The fact that coarse clastic deposits of Jurassic age border this belt on both the east and the west appears to indicate that a land axis existed in Jurassic time between the eastern and western areas of Jurassic sedimentation. This land has been termed the Cordilleran intermontane geanticline. The area of repeated marine inundation on the west is known as the Pacific geosyncline and that on the east as the Rocky Mountain geosyncline. During the

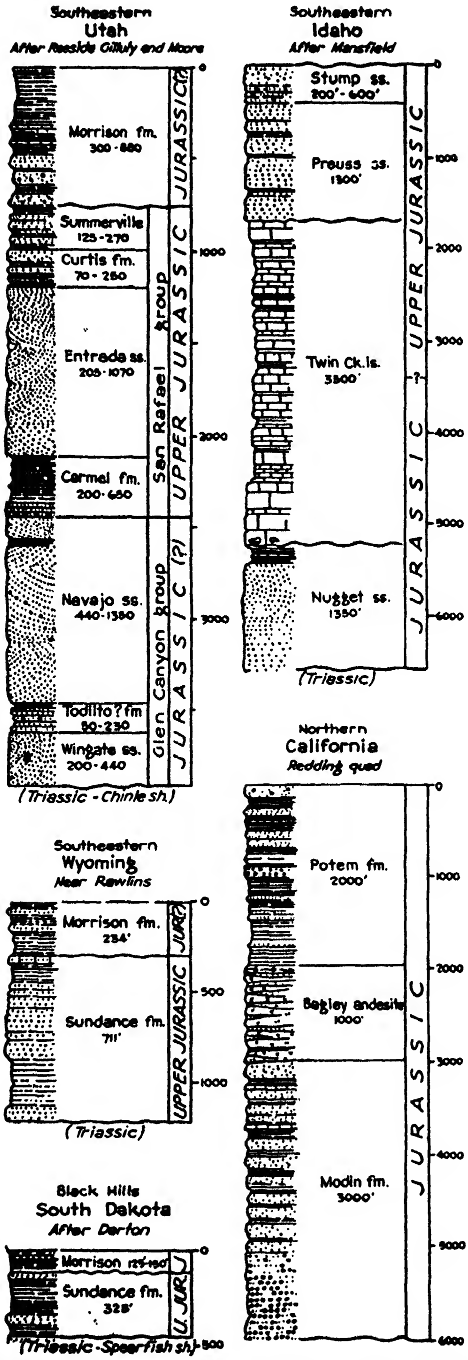

FIG. 252.—Generalized sections of the Jurassic system in Utah, Wyoming, South Dakota, Idaho, and California.

Jurassic period, waters from the Pacific gained access to the eastern geosynclinal area by a passage around the northern end of the Cordilleran intermontane geanticline, but the enlargement of this land in Late Jurassic time served to prevent later incursions from the Pacific from entering the Rocky Mountain geosyncline.

The Jurassic rocks of the Coast Ranges of California are difficult to study because of their complexity of structure, variation in lithologic character, and paucity of fossils. They have been commonly grouped under the name Franciscan series, derived from altered sandstones and other sediments in the San Francisco region. It is now becoming evident that the greatly disturbed, in part strongly metamorphosed pre-Cretaceous rocks of the Coast Ranges are not all Jurassic, and, although not likely, it is barely possible that the type Franciscan, in which no fossils have been discovered, is not Jurassic. The Jurassic fossils that have been found locally prove that rocks of this age occur in the Coast Ranges.

The thickness of Jurassic formations in the Pacific Border region shows much variation. A maximum of about 5,000 feet of beds is recorded from central British Columbia, 18,000 feet in western British Columbia, and 6,000 feet in northern California. The last figures do not take account of a reported thickness of 9,000 feet of Middle Jurassic volcanic rocks in Placer County, northern California (Crickmay).

Gulf Region

Widely scattered small outcrops of Jurassic rocks occur in Mexico, in the Malone Mountains of southwestern Texas, and in western Cuba. The rocks are mostly limestone, but clay shale and sandy beds also occur. The Texas Jurassic, which belongs to the upper part of the system, is reported to exceed 1,200 feet. Lower Jurassic beds unconformably overlaid by Upper Jurassic rocks are found in southern Mexico. These deposits of the Gulf region are marine and represent a transgression of waters belonging to the Mediterranean province of Jurassic time, rather than the Boreal province which is represented in the Western Interior and Pacific Border regions. The fossils, which are numerous in some beds, correspond closely to species from the Jurassic formations of southwestern and southern Europe and the Tethys geosyncline of Asia.

Igneous Rocks

Besides eruptive materials that are found in Jurassic formations of the Pacific Border region, the western part of North America contains large areas in which deep-seated igneous rocks of Jurassic age are exposed. As a matter of fact, these outcrops, which cover several thousand square miles, exceed in extent all of the exposures of sedimentary Jurassic rocks put together. With some interruption, the igneous-rock exposures reach

from Lower California and the mainland of western Mexico to Alaska. Rather vividly colored, they are prominent on the geologic map. The rocks are granitic in appearance but are more basic in character than granite and are called granodiorite or quartz monzonite. They were intruded into Jurassic and other rocks in the closing stages of the Jurassic period and are evidently related to the mountain-making disturbances that affected the Pacific region at these times. Their present exposure is clearly due to post-Jurassic erosion. As a result of elevation in very recent geologic history, the Sierra Nevada portion of the Jurassic granodiorite masses contains the highest mountain in the United States outside Alaska; this is Mount Whitney, 14,502 feet.

The great mass of "granite" and other crystalline rocks that forms the core of the Sierra Nevadas, Cascades, and other mountain ranges of the west involved in post-Jurassic deformation are certainly not all assignable to igneous invasions belonging near the close of Jurassic time. Carboniferous batholiths are recognized, and some of the crystalline rocks are very possibly, if not probably, of pre-Cambrian age.

JURASSIC FORMATIONS OF OTHER CONTINENTS

Deposits of Jurassic age are recognized in all of the continents including Antarctica and in most cases both marine and continental formations occur, the latter coal-bearing in parts of Europe, Asia, Australia, and elsewhere.

Europe.—Jurassic rocks are especially important in western and southern Europe. Marine limestone occurs at the base of the system in the Mediterranean region, indicating persistence of the general conditions that had existed here in the Triassic period. Northwestern Europe, including much of Germany, France, and the British Isles, shows dark-colored marine shaly rocks (Lias) resting unconformably on continental Upper Triassic. The Early Jurassic sea thus covered much territory that had previously been land. Many kinds of marine organisms are found, among them remarkably preserved reptile skeletons with bones in place, which are prized exhibits in museums.

The Middle Jurassic consists largely of oolitic limestone in England, sandstone and iron oolites in southern Germany, and of fairly pure, bedded limestone in France and the Mediterranean region generally. Marine rocks of this age occur in much of northern Russia. Many features indicate shallow-water deposition and there was considerable local oscillation. Continental beds with coal occur in Scotland.

Upper Jurassic rocks are mostly calcareous, in both northern and southern Europe. In Great Britain, oolite is prominent; one of the formations is known as the Coral rag on account of abundance of fossil corals. The Upper Jurassic limestones of southern Germany contain many reeflike masses that are composed chiefly of sponges, calcareous algae, and pelecypod shells. Lagoonal limestone deposits of exceptionally fine texture and even thin bedding occur in association with these reefs. Remains of marine animals and also flying land animals are very perfectly preserved in this rock, which originally was an impalpable soft ooze. Quarries at Solnhofen, in Germany, are world-famous on account of the unusually fine fossils collected there. Among these are the two only known specimens of the oldest fossil birds. The uppermost Jurassic contains fresh-water deposits in England and northern Germany, but marine calcareous beds continue to the top of the system in the Mediterranean

and Russian regions. The Rock of Gibraltar, at the entrance to the Mediterranean, is an eroded fault block of Jurassic limestone.

Asia.—Jurassic rocks are especially widespread in Asia. Much of Siberia and northern China contain continental Lower Jurassic deposits with coal, but on the Arctic and Pacific Borders, and also in the Caucasus region, rocks of this age are marine. Middle Jurassic beds in India and Upper Jurassic marine strata covering vast areas in the northeast and southwest parts of the continent are recorded.

PHYSICAL HISTORY OF JURASSIC TIME

The distribution and character of the Jurassic rocks, including especially evidence derived from the fossil remains of land and sea life contained in these rocks, furnish the data on which an account of the history of the Jurassic period must be based. The record in North America is much less complete than in Europe but the incompleteness itself has significance as to conditions on this continent. We should be much more poorly prepared, however, to understand the American Jurassic if the European section were unknown.

Erosion.—Viewed broadly, the Jurassic was a time of continental emergence in North America. Erosion exceeded deposition as regards

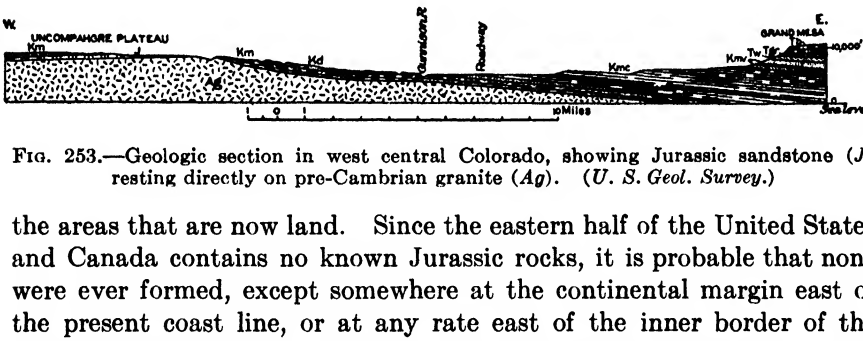

Fig. 253.—Geologic section in west central Colorado, showing Jurassic sandstone (*J*) resting directly on pre-Cambrian granite (*Ag*). (*U. S. Geol. Survey.*)

the areas that are now land. Since the eastern half of the United States and Canada contains no known Jurassic rocks, it is probable that none were ever formed, except somewhere at the continental margin east of the present coast line, or at any rate east of the inner border of the Coastal Plain. We find evidence of much erosion in the parts of the Appalachian area where very thick Triassic deposits had been formed, because the Triassic and adjoining pre-Triassic rocks were strongly elevated, with tilting and faulting of the Triassic formations, and then base-leveled before the beginning of Early Cretaceous sedimentation. The peneplain thus formed is designated the Fall Zone peneplain (D. W. Johnson) (see Figs. 241 and 332). Widespread erosion of all eastern North America in Jurassic time may be assumed confidently, but it does not follow necessarily that this erosion removed great quantities of Paleozoic and older rocks. The extent to which streams may denude a region depends on the position of the land surface with respect to base level. Accordingly, if the land of Jurassic time was low—and except in the Appalachians, elevation could only have been very moderate—little effect quantitatively can be expected from either widespread or prolonged erosion. About all that can be said is that the gently warped

Paleozoic formations west of the Appalachian Mountains and the complexly folded and faulted rocks of the mountains also were very smoothly beveled by the work of streams during Mesozoic time. Much of this erosion belongs to the Jurassic period.

The basal Lower Cretaceous rocks in Arkansas, Oklahoma, and Texas rest on an even surface that cuts across Paleozoic formations ranging in age from Pennsylvanian to Cambrian and that in a few places is carved on pre-Cambrian rocks. This erosion surface is a well-developed peneplain that was formed during the interval from Pennsylvanian to early Lower Cretaceous time. Probably the time of peneplanation may be assigned largely to the Jurassic period.

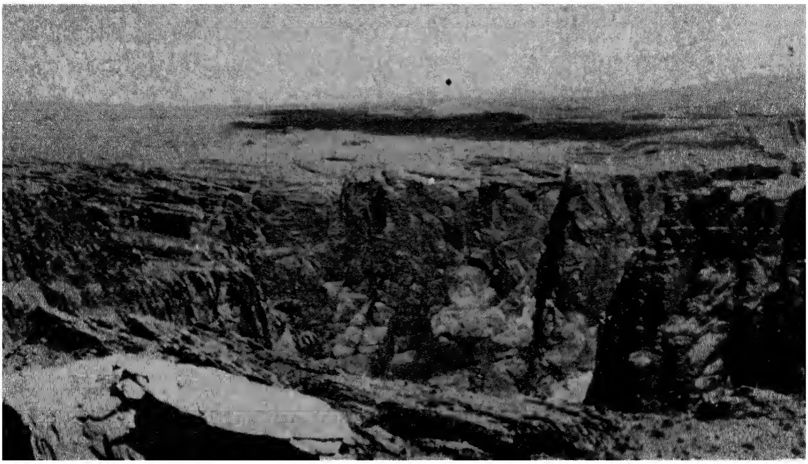

FIG. 254A.—A modern waste of bare rock and sand laid on the foundation of a Jurassic desert.

The western part of North America, including especially territory that now belongs to the Great Basin, must have been eroded greatly, for it appears that most of the thick sandy deposits of Jurassic age in the Colorado Plateau country came from there. Similarly, the thick sandy and shaly rocks, including some conglomerate, that comprise the Jurassic of the Pacific Border were probably derived from erosion of near-by uplands. In California the local Paleozoic source of some of the Jurassic sediments is established.

Continental Sedimentation.—If the highly cross-bedded sandstones that form so large a part of the Jurassic deposits in the Colorado Plateau country are rightly identified as continental deposits, we must conclude that great desert areas existed in the southwestern United States in Jurassic time. The prevalence of the cross-bedding and its large scale indicate wind work. There is also evidence of stream deposition in widespread very irregularly bedded sandstone, shale, and gravel beds, which occur in the midst of the cross-bedded sand deposits. We may

infer, therefore, that after a time in the early part of the Jurassic period, when desert conditions were dominant, there was an interval of greater rainfall when streams (probably originating mainly in the Colorado country) encroached on the dune-sand areas, reworking some of the sand and spreading it out with other detritus to form a sandy fluvial plain. The fact that the thick western part of the Jurassic sand deposits lacks these stream-borne beds suggests that the water disappeared by soaking into the porous sand and by evaporation before it reached this region. Similar conditions may be seen today at the margins of certain deserts.

After the Medial and Late Jurassic marine invasions that submerged parts of the Western Interior region, there was an interval of erosion and

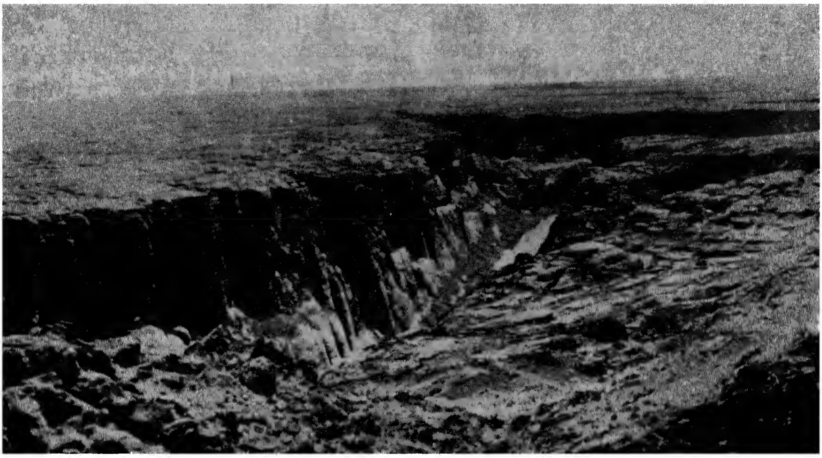

FIG. 254B. Continuation of 254A. Glen Canyon of Colorado River carved in massive Lower Jurassic sandstone. Near Lees Ferry, Ariz. (*E. C. La Rue, U. S. Geol. Survey.*)

then the very extensive deposition of Morrison sediments. The lithologic character and irregular bedding of this formation indicate that it is mainly the work of streams, but parts of it are possibly of lake origin. The physiography of this ancient time is too little known to permit definite statement as to the attitude of the land surface which influenced the direction of flow of the Morrison streams and which might indicate the chief source regions of the Morrison sediments. There is some evidence in the occurrence of remnants of this formation resting on pre-Cambrian rocks in Colorado, and in the distribution and thickness of the formation, that a part of the Morrison streams may have radiated from the Colorado region.

Marine Sedimentation.—The Pacific sea invaded California, western Nevada, and certain northerly parts of the coastal region very early in the Jurassic period and later spread repeatedly over the western part of the continent. In most places, muds and sands rather than limestones were deposited. Some of the adjacent land must have been moderately

elevated and it was possibly pushed upward several times, as indicated by the nature and thickness of the sediments derived from it. There were numerous volcanoes near the Pacific seas in the middle and late parts of the period. Much igneous matter ejected from these vents was carried by wind and streams to the sea.

Beginning in early Medial Jurassic time, but reaching greatest development in the later part of the period, a great embayment was formed that extended from British Columbia southward to Arizona and eastward to South Dakota. There was not a single slow advance and retreat of the sea in this region, but, instead, there is evidence of several wide expansions and withdrawals which did not coincide in extent. The waters that spread over this territory were connected with the Pacific and at times with the Arctic also. The sediments in the shallow Western Interior sea are mostly fine sandy and shaly material but there are also some limestone beds. The Twin Creek formation of northern Utah and southwestern Wyoming is made up largely of limestone and is nearly 2,000 feet thick.

The Jurassic deposits of Mexico show that a sea, of Mediterranean rather than Boreal origin, invaded that region early in the period and advanced to southwest Texas in the late part.

Climate.—Evidence of the climatic conditions in Jurassic time is found partly in lithologic but mainly in biologic characters. Variation regionally and changes with lapse of time are to be expected and are clearly indicated. Thus we find contemporaneous deposits that were apparently formed in a warm dry environment, in warm or cool humid surroundings, and in regions subject to definite seasons. We also observe indications of these contrasting climates in the successive deposits of a single district.

Generally cool climates in the Early Jurassic are inferred from the great restriction of some kinds of animals, and profound changes which are seen especially in the ammonites among marine invertebrates and the evolution of reptiles on land; also, there is a uniform dwarfing of insect species and well-developed seasonal banding is found in trees. Warm, widely uniform marine conditions in the middle part of later Jurassic time are shown by the abundance and very extensive distribution of the life of the seas. Ammonites were extraordinarily numerous and lived abundantly in polar as well as equatorial latitudes. Corals are common in the far north. The land flora, including many plants of subtropical appearance, is much the same in England, Alaska, California, and Antarctica. Near the close of the period, however, the plants indicate, in some places at least, moderate temperatures and strong seasonal variations.

Close of the Period.—The termination of Jurassic time is marked by elevation of North America and other continents, causing the nearly

complete withdrawal of seas to the oceanic basins. It was a time of mountain-building also, for the western part of North America from Mexico to Alaska was very strongly compressed. Mountains occupying the general position of the modern Sierra Nevadas, Klamaths, Cascades, and Coast Ranges were elevated in the California-Oregon-Washington region, parts of westernmost Canada, and the country of the Alaskan Coast Ranges farther north. This is shown by the structural complexity of pre-Cretaceous rocks throughout this territory,

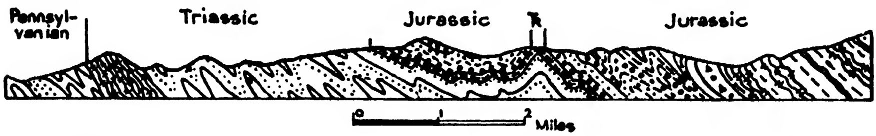

FIG. 255.—Geologic section showing structure of a part of the Sierra Nevada Mountains in California about 60 miles northeast of Sacramento. The folding of the Carboniferous beds is partly pre-Jurassic, as shown by the angular unconformity at the base of the Jurassic system. (*U. S. Geol. Survey.*)

as compared with the structure of unconformably overlying Cretaceous rocks. The older formations were folded, faulted, and intruded by igneous rocks and then deeply eroded before the beginning of Cretaceous sedimentation. There were disturbances in Cretaceous and later time that have further complicated the geologic structures. There is no indication that the mountain ranges existing today were differentiated at the time of Jurassic mountain-building. Pronounced folding took place in Asia at the close of the Jurassic period. As a result of this diastrophism, which may be designated as the *Jurasside disturbance*, the Jurassic and older rocks were steeply folded, faulted, and in

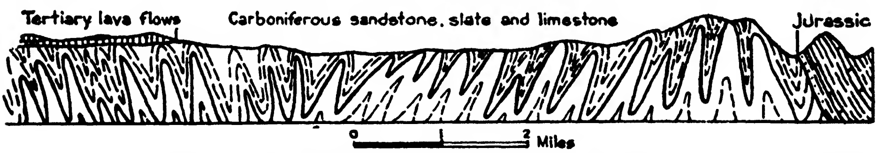

FIG. 256.—Folded strata in the Klamath Mountains of northern California (Redding quadrangle). The deformation of this region belongs partly to the Jurasside disturbance. (*U. S. Geol. Survey.*)

places metamorphosed. Large thrust faults in southern Nevada indicate eastward movement of the overthrust blocks amounting to several miles. Recent studies indicate that some of the crustal deformation in this region belongs to early Late Jurassic time.

Associated with the mountain-building was the very extensive intrusion of igneous rocks which has been noted previously. The great igneous masses are batholiths that cooled slowly at considerable depth below the surface, thus developing the coarse texture that is typical of such plutonic intrusions. Subsequently, when erosion had removed the rock above the batholiths, the latter were exposed, and an unknown quantity of the

igneous rock has now been carried away. The present topographic relief in these western mountains is wholly due to uplifts of comparatively recent geologic date, long after the deformation and intrusion that gave rise to the Jurassic mountains.

ECONOMIC PRODUCTS

Gold-bearing veins related in origin to the great igneous activity of closing Jurassic time occur in the Sierra Nevada region of California. The veins follow planes of weakness in the Jurassic slaty rocks (Mariposa slate) and other formations. Some of the veins, like the famous Mother Lode, have yielded millions of dollars in gold. Weathering of the veins frees the gold particles and nuggets which are concentrated because of their high specific gravity in the beds of streams. Thus many rich placer gold deposits have been formed.

Coal is an important deposit in Jurassic rocks except in North America. The chief occurrences are in central Europe (Hungary) and Asia (Siberia, China, India).

SUMMARY

The Jurassic system, named from the Jura Mountains of central Europe, is best developed and has been most carefully studied in Europe. The formations here are wonderfully fossiliferous and are divisible into minute, widely traceable stratigraphic units. The Jurassic is distinguished from other parts of the Mesozoic by its fossils, by differences in lithologic character, and by unconformities at the bottom and top.

North America contains Jurassic deposits only in the western half of the continent. (1) The Western Interior region shows thick unfossiliferous cross-bedded sandstones that are regarded as wind-blown in origin. They are associated with some thinner stream-laid beds and in the upper part of the section are extensive marine formations containing Jurassic fossils. The youngest Jurassic (?) consists of stream deposits (Morrison) that rest unconformably on older rocks and are unconformably succeeded by Cretaceous. The Jurassic strata are vividly colored and topographically prominent. (2) The Pacific Border region contains Jurassic deposits up to 18,000 feet in thickness, mostly marine, and representing in various parts the lower, middle, and upper subdivisions of the system. Contemporaneous volcanic activity, especially in the medial and late parts of the period, is shown by tuffaceous and other igneous material in some of the formations. Present structure of these rocks is mostly very complex. (3) The Gulf region, comprising parts of Mexico and southwestern Texas, has marine Jurassic formations that are of Mediterranean rather than Boreal affinities.

Enormous batholiths of granodiorite and similar rock occur in western North America from Mexico to Alaska. Their present outcrops are larger in extent than that of all of the sedimentary Jurassic formations combined.

The European Jurassic is made up mainly of dark bituminous shaly rocks in the lower part (Black Jura), ferruginous oolites and sandy beds

in the middle (Brown Jura), and light-colored limestones in the upper part (White Jura). Abundance of beautifully preserved fossils, occurrence of coral and other types of reefs, prominence of oolite, and presence of important coal beds are outstanding features of the system.

Study of the distribution and character of the Jurassic rocks permits inference of the physical history of the period, calling attention to indications of (1) erosion throughout the eastern part of North America in which post-Triassic mountains were obliterated and an extensive peneplain was produced; (2) continental sedimentation in the Western Interior region, occupying probably most of the early and medial parts of the period and including formation of enormous quantities of wind-

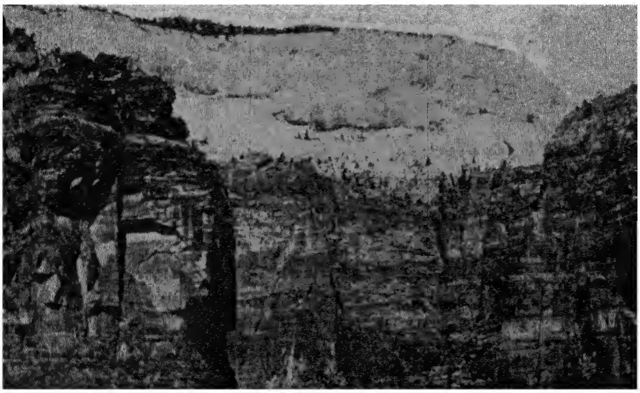

FIG. 257.—Red and nearly white Jurassic sandstone in Zion National Park. (*W. T. Lee, U. S. Geol. Survey.*)

borne sand and of stream-carried sediments, the latter being prominent also toward the close of the period; and (3) marine sedimentation of various sorts, marking the advance of shallow seas from different oceanic basins. There was great volcanic activity along the Pacific Border. The latter part of the period, and especially its close, was marked by crustal unrest, continents being elevated and mountains being formed. The most important effects of this diastrophism (Jurasside disturbance) are seen in western North America and Asia. The mountain-making resulted in complex folding and faulting, and in metamorphism of the sedimentary rocks. Intrusion of batholiths on a large scale accompanied the deformation. Erosion of the mountainous areas and of other parts of the continent where Jurassic sedimentation has occurred completes the record of geologic history to the beginning of Cretaceous deposition.

CHAPTER XXIV

FORMATIONS AND PHYSICAL HISTORY OF CRETACEOUS TIME

The latter part of the Mesozoic era has come to be known as the Cretaceous period, for chalk (Latin, *creta*) is a prominent constituent in the marine deposits of this age, not only in Europe, where the name was introduced, but in other continents. The cliffs of white chalk that occur on both sides of the English Channel are particularly striking. Because of this prominence of chalk in many places and because chalk is almost restricted to the Cretaceous system, the name of the period and system seems appropriate. The fact, however, that Cretaceous formations in many regions contain no chalk and the general preponderance of shale and sandstone in the deposits as a whole make the term less fitting. Like "Carboniferous," the name is lithologic rather than geographic in origin, but through sanction of long usage it is very firmly established.

Definition and General Character.—Concerning the great majority of Cretaceous rocks no question as to age arises. The marine and non-marine strata of the Cretaceous and contiguous systems mostly contain distinctive fossils that provide means of definite recognition. In places, however, the exact position of the bottom and in others that of the top are in doubt. These difficulties in precise definition of the boundaries of the system apply particularly to the Western Interior region of the United States. A widespread continental formation of variegated color and lithologic character (Morrison) which has yielded numerous remains of giant reptiles and some other fossils is probably of Late Jurassic age but is regarded by some geologists as belonging to a very early part of the Cretaceous period. There is an important unconformity at its base, but a still more important one above it, the latter being now considered to mark the division line between the Jurassic and Cretaceous systems. The location of the boundary between Cretaceous and Tertiary in many parts of the Rocky Mountain region is a vexatious question that has been the subject of much controversy. It comprises the so-called "Laramie problem," which will be considered in more detail later in this chapter. At most places in the Atlantic and Gulf Coastal Plains areas and on the Pacific Border the oldest Tertiary rests unconformably on Cretaceous or older rocks.

The Cretaceous formations are composed of shale, sandstone, chalk or chalky limestone, conglomerate, and coal, named in the approximate

order of quantitative importance. In some areas there are considerable amounts of igneous materials that have been reworked by sedimentary agencies. The shale formations of Cretaceous age are clayey, calcareous, or sandy. Several of them are noteworthy on account of their extremely wide area of distribution and their remarkably uniform lithologic character. In parts of the Western Interior of North America there are shale deposits 4,000 feet or more in thickness uninterrupted by other kinds of rock. The shale is mostly dark-colored, drab-gray to nearly black, but there are some light and varicolored beds.

Sandstone and, locally, conglomerate are very important types of rock in the Cretaceous deposits. Some of the sandstones, notably the

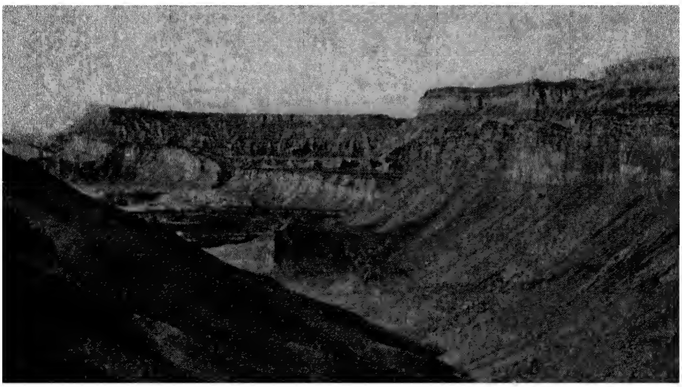

FIG. 258.—Cretaceous sandstone and shale, south of San Rafael Swell, near Caineville, Utah. (*E. M. Spieker, U. S. Geol. Survey.*)

Dakota, are surprisingly extensive geographically, and they exert a marked influence on topography and vegetation. Some of them have much economic importance as containers of oil, gas, or fresh water. In Colorado, Utah, New Mexico, and several other western states, Cretaceous sandstones make lofty table-lands and buttes with cliff margins.

Chalk is most prominent in the upper part of the Cretaceous section in the Gulf and Prairie Plains country, but there is very much chalky or hard limestone in the Lower Cretaceous, especially in Louisiana, Texas, and Mexico. The chalk is bluish-white to light creamy-yellow in color, in strong contrast to the dark-colored shale, but, because of the softness of the rock, outcrops are not generally very numerous. The chalk tends to make rounded grass-covered hills. Some of the limestones, however, are sufficiently strong to form prominent escarpments and extensive uplands.

Next to the Pennsylvanian, Cretaceous formations are the most important in content of coal. There are many different beds, some of which are 30 feet or more in thickness. The area of workable coal beds in the Cretaceous strata covers many tens of thousands of square miles.

CRETACEOUS FORMATIONS OF NORTH AMERICA

Distribution.—Deposits of Cretaceous age are found in North America (1) along the inner border of the Atlantic Coastal Plain, (2) in the Gulf Coastal Plain region, (3) in a very great part of the Western Interior of the continent, including the Rocky Mountain area, the adjacent portion of the plains to the east, the plateau country to the west, and much of

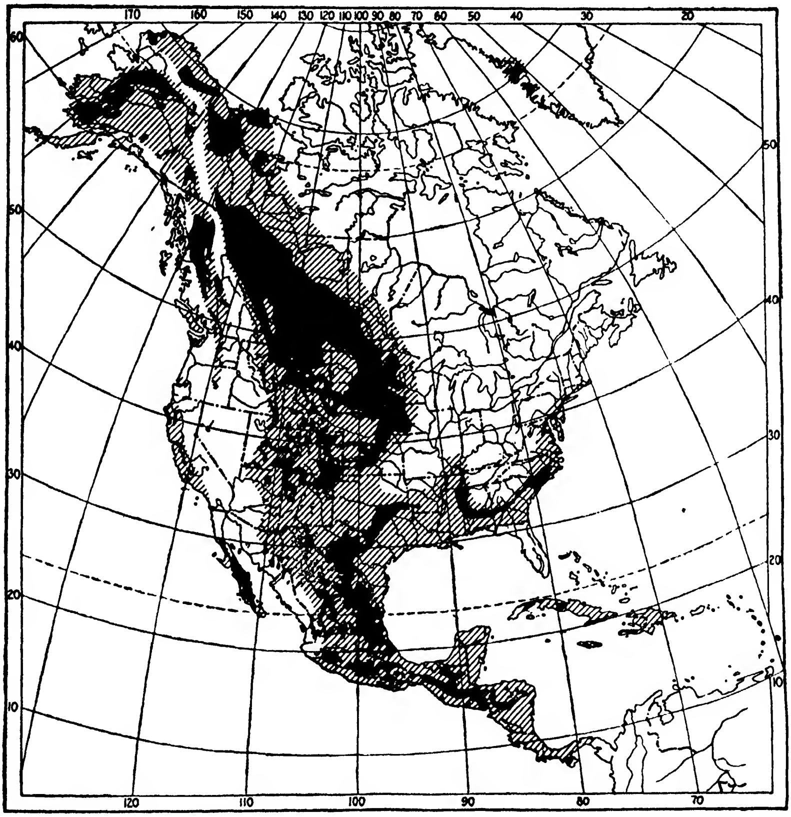

Fig. 259.—Map of North America showing outcrop areas of the Cretaceous system (black) and the inferred area of original distribution of Cretaceous formations. (*V. R. D. Kirkham, in Chamberlin and Salisbury's Historical Geology, Henry Holt & Company.*)

northern Mexico, and (4) in a belt near the Pacific. Formations in the Atlantic region have a maximum exposed thickness of a little less than 2,000 feet; in the Gulf, about 9,500 feet; in parts of the Western Interior, 14,000 feet; and in the Pacific region, nearly 30,000 feet. Hence, the Cretaceous rocks in aggregate are much the thickest and most extensive of the Mesozoic systems in North America. Marine sediments are relatively much more important than in the Triassic or Jurassic system.

Classification.—The Cretaceous rocks are readily divisible into two major parts or series. The older of these is called the Lower Cretaceous,

and the younger, the Upper Cretaceous. The name Comanchean, which has been much used in American texts as equivalent to Lower Cretaceous, and the less common term Gulfian, for Upper Cretaceous, are not properly applicable in this general sense.[1]

TABLE OF CRETACEOUS STRATIGRAPHIC DIVISIONS OF EUROPE AND THEIR AMERICAN EQUIVALENTS

Europe		North America			
Danian		Lance Laramie		Gulf	Navarro
Maestrichtian		Montana	Fox Hills		Taylor
Senonian	Campanian		Pierre		
	Santonian	Colorado	Niobrara		Austin
	Coniacian (Emscherian)		Benton		Eagle Ford
Turonian		Dakota			Woodbine
Cenomanian				Comanche	Washita
Albian		Kootenai			Fredericksburg
Aptian					Trinity
Neocomian	Barremian				
	Hauterivian				
	Valanginian				
	Berriasian				

In each region of Cretaceous rocks there is necessarily variation in the detailed classification of the deposits. Many local names are applied to formations. Accumulating knowledge of the character and distribution of fossils is affording basis for definite correlations but the majority of local stratigraphic names will continue to be used because they distinguish variations in the nature of the deposits.

[1] The main reasons for this are that Comanchean represents only a part of Lower Cretaceous, that the line of division between Comanchean and Gulfian is apparently different from that between Lower and Upper Cretaceous, and that the latter names have world-wide application and long usage.

Atlantic Border Region

In the eastern United States, Cretaceous strata form a part of the Atlantic Coastal Plain. The outcrops extend in a narrow belt from Martha's Vineyard, east of Long Island, southwestward across New Jersey, part of Delaware, Maryland, Virginia, the Carolinas, and Georgia. The outcrop belt forms the inner edge of the Coastal Plain, except in a few places, as in Virginia especially, where Tertiary deposits overlap and conceal the Cretaceous. The Cretaceous rests unconformably on pre-Cambrian rocks or, in places, on Paleozoic or Triassic beds. It is overlaid unconformably by the Tertiary. Although Jurassic rocks are not known in this region, it is altogether probable that seaward from the Cretaceous outcrop at some distance the Cretaceous rests on Jurassic sediments.

The surface beneath the Cretaceous deposits of the Atlantic region has a maximum relief of about 300 feet, which shows that pre-Cretaceous erosion had reduced this part of the continent to a gentle plain (Fall Zone peneplain), even though the presence of many resistant rock formations retarded erosion. The change from conditions favoring erosion to those resulting in deposition of the Cretaceous sediments implies an upward movement of the earth crust in the Appalachian region that rejuvenated streams and accelerated erosion, while sedimentation occurred in the lower country farther east where Cretaceous beds are now found.

Lower Cretaceous Rocks.—The exposed Lower Cretaceous formations (Potomac group) consist entirely of continental sediments, stream-borne or of swamp origin. There are irregularly bedded deposits of sandstone, gravel, clay, and some lignite. Presence of feldspar fragments in the sands, and of pebbles of schist and other crystalline rocks in the occasional gravel beds, indicates that stream erosion in the areas from which the sediments were derived proceeded faster than decomposition by chemical weathering. The chief type of deposit is an unconsolidated sandy clay. Clay ironstone is locally abundant and has been mined as an iron ore; oxidation of iron gives many of the beds a strong reddish brown color. Disconformities and differences in lithology and fossils serve to separate three formations. The lowermost (Patuxent) consists largely of coarse materials; the middle (Arundel), composed mainly of dark clays, contains some lignite; the upper (Patapsco) is sandy and variegated in character. Judged by fossil plants, the hiatus between the middle and upper formations is considerably greater than that between the lower and middle formations. The maximum thickness of the Lower Cretaceous deposits, about 700 feet, is found in Maryland.

Although marine Lower Cretaceous strata are not known in the Atlantic region even in near-coast wells that penetrate crystalline rocks

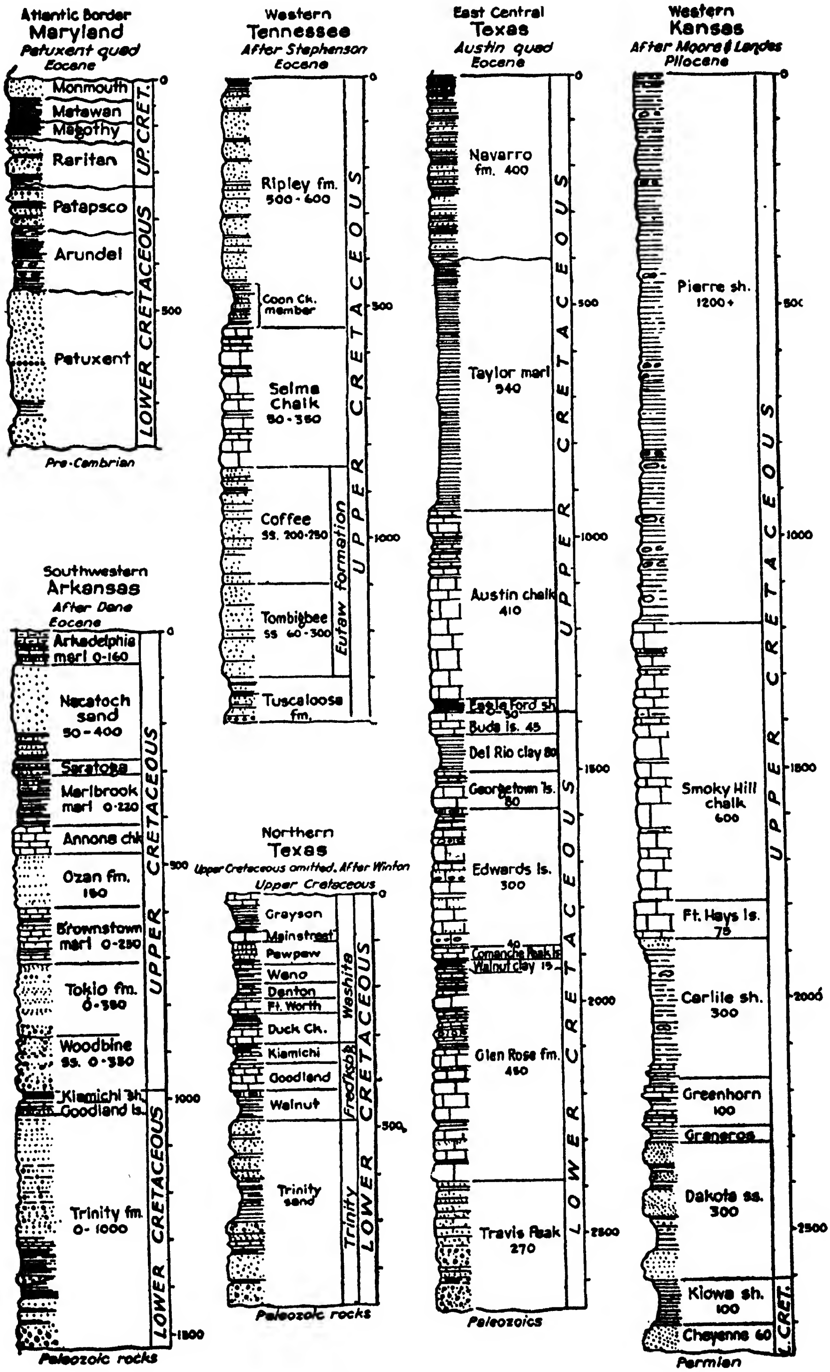

FIG. 260.—Generalized sections of the Cretaceous system in selected areas.

beneath all sediments, they are assuredly present in a seaward direction beneath parts of the Upper Cretaceous and Tertiary strata. It is probable that no marine Lower Cretaceous underlies any part of the present Coastal Plain, being absent either because the sea at this time did not invade the depression between a persisting remnant of Appalachia and the mainland (Grabau) or, if there was no such remnant of Appalachia, because the sea margin of Early Cretaceous time lay east of the present coast line.

Upper Cretaceous Rocks.—Beds of Late Cretaceous age are present in the Atlantic region. They crop out in a belt adjoining and parallel to that of the Lower Cretaceous, and, since all of these strata dip seaward (at about 40 feet to the mile), the younger or Upper Cretaceous belt is on the seaward side of the Lower Cretaceous outcrop. The basal Upper Cretaceous formation is a continental sand (Raritan) which has a thickness in places of 400 feet. Associated with this formation are beds of gravel, clay, and lignite. The succeeding Cretaceous rocks, 600 to 800 feet thick, consist of clays and sands that are mostly of marine origin. Glauconite or greensand is especially common. These beds belong to the latest parts of the Cretaceous, as clearly shown by their fossils. The disconformity at their base thus represents much of early and medial Late Cretaceous time.

Gulf Region

The Cretaceous of the Coastal Plain region adjoining the Gulf of Mexico is exposed at the surface in a curving belt which on the east side of the Mississippi swings southeastward from the mouth of the Ohio River into Georgia. West of the Mississippi, the belt is traced from southeastern Arkansas southwestward across southern Oklahoma, northern and central Texas, into Mexico. The Cretaceous rocks are concealed by later deposits in eastern Arkansas, but in parts of the Texas region the surface exposures become very wide, more than 100 miles across in places.

Description of the Cretaceous formations of the Gulf region may be advantageously based mainly on the Texas section, which is thicker and much more complete than in the eastern part of the Gulf region. This is the type locality of the Comanche and Gulf series, which are distinguished by lithologic and faunal differences and are separated by a disconformity. Since the Cretaceous rocks dip gently in the direction of the Gulf, the Comanche outcrops are found on the side of the Cretaceous belt that is nearest the Continental Interior, and outcrops of the Gulf series on the side that is nearest to the coast.

The Comanche series comprises only the upper part of the Lower Cretaceous as known in Europe, Mexico, and some other regions, and it is thought that beds at the top are equivalent in age to the basal part of the Upper Cretaceous of Europe (see table, page 433). Thus, the

divisions of the strata in the Gulf region of the United States do not correspond precisely to Lower and Upper Cretaceous as generally defined but, including Mexican deposits, they do so approximately.

Comanche Series

Trinity Beds.—The basal part of the Comanche series consists of sand, in places associated with much conglomerate and in other places containing much limestone. These lowermost Cretaceous sediments, called Trinity or "basement sands," rest unconformably on a smooth, gently sloping erosion surface of Paleozoic and older rocks. For example, in southwestern Arkansas and southern Oklahoma the steeply folded Paleozoic rocks of the Ouachita and Arbuckle Mountains are truncated by the pre-Trinity peneplain, which here dips southward at an average rate of about 100 feet per mile. The sand and gravel that are found at

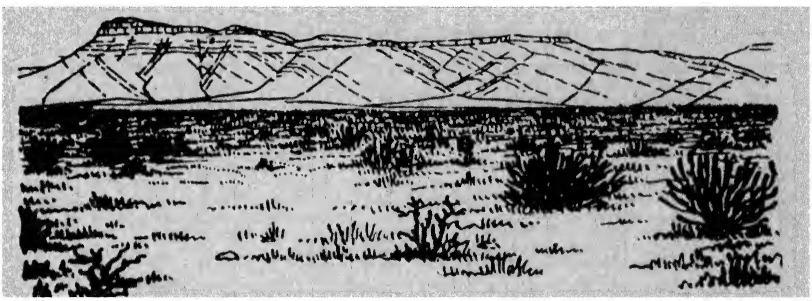

FIG. 261.—Unconformity between Comanchean rocks (capping the hills) and Permian rocks (inclined beds) in west Texas, near Tesnus. (*P. B. King, Texas Bur. Economic Geology.*)

the base of the Comanche series are some of the products of the extensive erosion of the older rocks.

The maximum thickness of Trinity deposits, about 2,000 feet, is found in southwestern Texas and in northwestern Louisiana (well borings), where also there is the greatest proportion of limestone. The limestone gradually becomes thinner northwestward, disappearing in northern Texas. Associated with the limestone is some anhydrite and gypsum, and in at least one part of southern Texas there are beds of rock salt. This indicates that the sea was locally so enclosed that evaporation caused precipitation of these minerals. There is possibility that the extensive sheet of salt beneath the Coastal Plain of eastern Texas and Louisiana, which is indicated by scores of pluglike salt intrusions in the Tertiary rocks, may be of Comanche age (Fig. 318).

In Arkansas and Oklahoma, the Trinity consists mostly of sand and conglomerate, but there are some thin limestone beds. One of these that is considerably above the base of the series in southwestern Arkansas is found to lie nearer and nearer the base when traced westward, and

finally to occur at the very bottom. Since the limestone bed was all deposited at essentially the same time, this means that the later Trinity sea extended farther westward, and probably also northward, than the early Trinity. In other words, the Trinity sea overlapped westward and probably northward.

Fredericksburg Beds.—A temporary recession of the sea, marked by southward spreading of sand at the top of the Trinity, by a disconformity in northern Texas and southern Oklahoma at this horizon, and by a considerable difference in the character of the fossils in the Trinity and next younger beds, terminates the first chapter of the Comanche record and introduces the second, which is called Fredericksburg. Formations of Fredericksburg age consist mainly of limestone, and they occur over a large area in the southwest. The limestones are 500 or more feet in thickness and are fairly hard, forming a plateau. In western Texas there are sands and clays with massive limestone in this part of the Comanche series, which attains a thickness of 1,500 feet. The Fredericksburg deposits become gradually thinner northward, being represented in northern Texas and southern Oklahoma by limestone (Goodland) that is only 15 to 50 feet thick. The Fredericksburg sea extended farther northward than the greatest advance of the Trinity sea, for pure limestone representing offshore deposits rests on near-shore sand and gravel of the Trinity. The northern margin of the original Fredericksburg deposits has been eroded, so that it is not now possible to determine how far these rocks once extended. Deposits of latest Fredericksburg age (?) (Kiamichi) are known as far north as Kansas and Colorado.

A prominent feature of the Fredericksburg beds in part of southwestern Texas and northern Mexico are reefs (bioherms) composed largely of the very peculiar, sedentary pelecypods called caprinids and rudistids (Fig. 294), associated with corals, large foraminifera and broken shells.

Washita Beds.—The upper part of the Comanche series is called the Washita group. The rocks of this age in the Gulf region consist of alternating thin formations of limestone, shale, and sandstone. The limestone beds are mostly nodular, marly, and rather soft and contain numerous well-preserved fossils. The shales are clayey, calcareous, and in part sandy; some of the beds are very fossiliferous. Washita deposits are known as far northwestward as Colorado, but farther east the late Comanche sea does not appear to have advanced northward beyond southern Oklahoma or eastward much beyond the Mississippi River.

Transgressive overlap of the Comanche beds that is associated with the gradual northward invasion of the Early Cretaceous sea in the Gulf region is an important feature in the stratigraphy and historical geology of these rocks. The earliest Cretaceous occurs in Mexico, and in this region is found the greatest thickness of Cretaceous rocks, almost all of which consists of limestone. Thus, the sea came first into the Mexican

part of the Gulf region and occupied it most continuously. The sediments there are nearly all of clear-water, offshore type. The Trinity is thickest and made up most largely of massive limestone in the south, thinning northward and changing to sandstone and conglomerate. The Fredericksburg consists of thick limestone in the south, thins northward, and extends beyond the edge of the Trinity; the marginal deposits are mostly sand and clay. The Washita sea did not overlap the Fredericksburg except in a few places, but it also is much thicker in southwestern Texas than in the north. It is interesting to find that the basal Comanche deposits at any place are composed mostly of sand, whether they belong to the early, middle, or late part of the Trinity, or to Fredericksburg, or Washita.

Gulf Series

The Gulf series is separated from the Comanche series by a disconformity. In the region of the Sabine Uplift in northwestern Louisiana, the Washita, Fredericksburg, and part of the Trinity, are all missing, owing either to removal by erosion before the basal sand of the Gulf series was laid down, or possibly to nondeposition. Elsewhere, the presence of upper Washita strata shows an absence of much erosion at this time, even though there is physical evidence of interruption of sedimentation. The recession of the sea that is indicated by this disconformity, the ensuing great marine transgression which extended the domain of the sea far beyond the area covered at any previous time in the Cretaceous period, and the modification of life as shown by lack of fossil species common to the two series are reasons for separating the Comanche and Gulf beds.

Basal Sand.—At the base of the Gulf series in the northern part of the Gulf region is a sandstone (Woodbine) which makes a belt of timber-clad hills at the outcrop. The sand decreases in thickness southward, disappearing near Waco, Tex., and it pinches out on the flanks of the Sabine Uplift. It is of much economic importance as a container of oil and gas, especially in the great East Texas fields. There are clay and coal beds in parts of this formation. The presence of coal and of well-preserved fossil leaves indicates continental sedimentation, but occurrence of brackish water and marine shells in places proves deposition of parts of the formation in the sea.

Shale and Chalk Beds.—The next higher formation of the Gulf series is a widespread deposit of dark-colored clayey shale (Eagle Ford) with some thin beds of limestone in places. Its average thickness in Texas is about 150 feet. General uniformity of lithologic character and the persistence of certain fossil zones are noteworthy. Near Dallas, in northern Texas, the shale attains the maximum known thickness of about 500 feet, but a southward thinning reduces the formation to only 30 feet

near Austin. This thinning is apparently due in part to a retarded rate of sedimentation and in part to nondeposition, both of these conditions resulting from influence of the Llano Uplift in south central Texas. Farther southwest the shale thickens and becomes increasingly chalky.

The middle part of the Gulf series consists of light-blue or nearly pure-white chalk (Austin). Some of the chalk weathers to a very light creamy-tan, and thin layers of dark-bluish chalky shale are common. The formation is sufficiently hard to make a good escarpment at the outcrop. The average thickness is about 300 feet. Microscopic study of the chalk shows the presence of abundant very minute marine shells belonging to the protozoan group Foraminifera. These animals are very abundant in modern seas, in both moderately deep and shallow

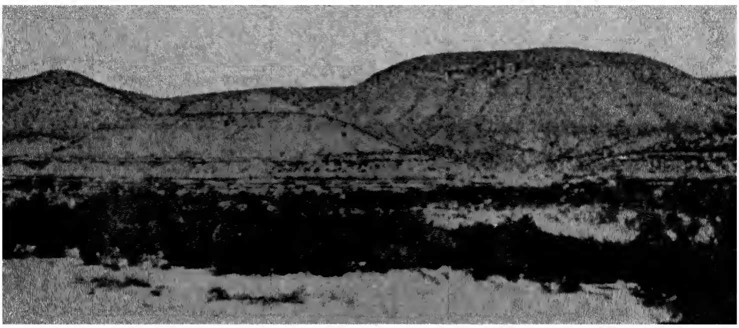

FIG. 262.—Upper Cretaceous shaly beds (Eagle Ford) resting on Lower Cretaceous limestone (Buda) near Sanderson, Tex. (*T. W. Stanton, U. S. Geol. Survey.*)

water. Because shells of this sort are most prominent in the deeper-water deposits, it has been assumed by some geologists that the Cretaceous chalk was deposited in fairly deep water, that is, 500 to 1,000 feet or more in depth. However, prominence of Foraminifera in deep-water deposits does not necessarily mean that these shells may not be equally abundant in shallow water, lesser prominence in the latter being due merely to the much greater quantity of other materials that are here admixed with the Foraminifera. If, because of very low or distant land areas, sediments of inorganic origin are small in amount, Foraminifera in a shallow sea, 50 to 500 feet deep, may contribute a relatively large quota to the sea deposits. The presence in the chalk of shells of distinctly shallow-water animals, especially certain pelecypods, and association of the chalk with shale and sandstone (locally cross-bedded) that are clearly of shallow sea origin favor the conclusion that the chalk beds are not deep-sea sediments.

Upper Beds.—The upper portion of the Gulf series in the Gulf Coastal Plain consists mostly of shale or marl (Taylor and Navarro). There are some beds of chalk, and in northeastern Texas and Louisiana

at least one persistent sand that is an important oil- and gas-containing bed. The beds are light-colored and they are soft and easily weathered, forming lowlands. The upper part of the Gulf series in southern Texas and adjacent parts of Mexico is about 4,000 feet thick. The beds consist largely of shale and sandstone and contain valuable coal deposits.

The Upper Cretaceous formations of Louisiana, southern Arkansas, and northeastern Texas contain much sand and volcanic materials at several horizons, which with other characters has led to use of formation names different from those of Texas, although equivalence in age is well established by means of fossils.

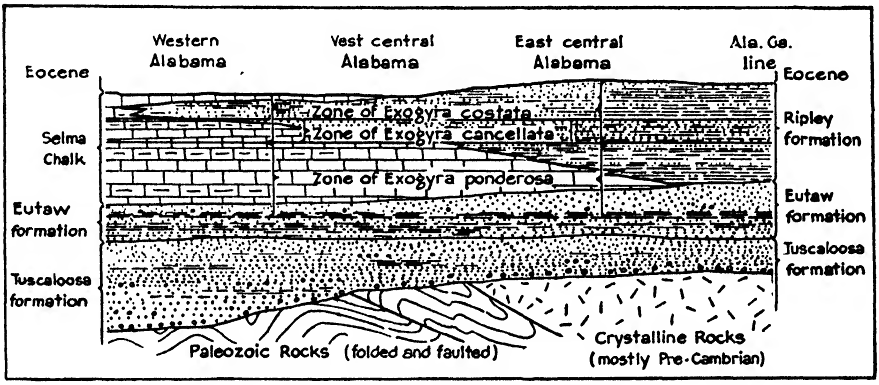

FIG. 263.—Diagram showing variation in types of contemporaneous sedimentation in the Upper Cretaceous series of Alabama. The zones of guide fossils are shown. (*After L. W. Stephenson, U. S. Geol. Survey.*)

Eastern Part of Gulf Region.—From southernmost Illinois near the mouth of the Ohio River, outcrops of Cretaceous rocks extend southward across western Kentucky and Tennessee, the northeastern corner of Mississippi, and obliquely southeastward and eastward across central Alabama into Georgia. The rocks belong to the Gulf series, the Comanche beds having been overlapped and concealed by the Upper Cretaceous deposits. It is not now known whether the Comanche sea invaded any of the Coastal Plain region east of the Mississippi, for beds of this age have not been identified in any deep wells, even including a Florida well 6,180 feet deep that reached crystalline (probably pre-Cambrian) rocks. The beds of the Gulf series rest unconformably on various Paleozoic formations, or in eastern Alabama and Georgia on pre-Cambrian crystallines. The Appalachian Mountains, with complexly folded and faulted structure, the strike of the folds trending northeast-southwest, disappear beneath the overlapping Cretaceous strata in Alabama. These mountains, which were formed near the close of Paleozoic time, had been worn down nearly smooth before the Cretaceous sea covered the southern parts of the range.

The Cretaceous deposits of this region consist largely of sand and sandy shale, but toward the west there is much impure chalk. The total thickness of these beds is about 2,400 feet. The basal formation is a nonmarine, locally lignite-bearing sand (Tuscaloosa), which in places contains gravel derived from the older rocks and also includes much clay. This formation is about 1,000 feet thick. The next higher beds are shallow-water marine sands (Eutaw) and some fresh- or brackish-water beds, about 400 feet in all. The overlying formation consists of chalk and chalky shale (Selma), except in eastern Alabama and western Tennessee where sandy shale and calcareous sand (Ripley) take the place of the chalk. The distribution of certain fossils, which mark successive stratigraphic zones, shows clearly that these different sorts of deposits in the upper Gulf series are equivalent (Fig. 263). Chalk was being deposited in one part of this region while clay and sand were being formed in another. The replacement of one kind of sediment by another laterally, and the persistence of the fossil zones, proves that the formations are contemporaneous.

Western Interior Region

The Cretaceous rocks of the Western Interior of the continent occupy an immense territory that reaches eastward to Iowa, westward to Utah and Idaho, and northward from the Gulf region to the Arctic Ocean, near the mouth of the Mackenzie. The sea that occupied this huge area constitutes much the largest inundation of the North American continent since Paleozoic times, and it is comparable with the very extensive flooding that occurred in the Ordovician period.

Except in part of the plains country east of the Rockies, the deposits consist almost wholly of shale and sandstone, dominantly marine but in a large part nonmarine. The average thickness is more than 3,000 feet and locally it exceeds 14,000 feet. Some of the sandstones, especially those at the base, are conglomeratic. Deposits of coal are widespread and of great economic importance. Almost all of the formations are of Late Cretaceous age.

Lower Cretaceous deposits, consisting of dark-colored shale and sandstone and locally of a little limestone, are known in Colorado (Purgatoire), in the Black Hills region of South Dakota and Wyoming (Lakota-Fuson), and in Montana and Alberta (Kootenai). These are mostly nonmarine beds representing continental sedimentation equivalent in age to part of the marine Comanche strata of the Gulf region. The maximum thickness of these beds is found in southern Alberta, where about 5,300 feet of sandstone, shale, and coal is measured. There are 22 workable coal beds with an aggregate thickness of 216 feet in part of this region, but the number and thickness of the coal beds, and the

thickness of the Lower Cretaceous deposits as a whole, decrease rapidly away from this area. The Lower Cretaceous of the Black Hills region also contains workable coal beds near Newcastle, Wyo. Marine sediments of Lower Cretaceous age in Kansas and Colorado were undoubtedly connected with those of the Gulf region.

Dakota Group.—The basal deposit of Late Cretaceous age in the Western Interior is a very extensive, irregularly bedded sandstone (Dakota), which is commonly stained dark brown by oxidation of iron. The rock is hard and accordingly makes prominent hills, escarpments, and mesas. Lenticular deposits of sandy shale, thin beds of coal and of conglomerate occur at many places. The sandstone is a chief source of water in parts of the plains country, but locally the formation contains enough salt to make the water unfit for use. The presence of salt, of marine and brackish water fossils, and of regular stratification in parts of the Dakota point clearly to a marine origin, but other parts have the form of stream channel fillings, contain abundant well-preserved leaves of land plants, and show other features, such as abundant irregular crossbedding, characteristic of continental deposits. There is evidence that the formation is not of the same age in all places but is simply the basal Upper Cretaceous deposit of stream-laid and sea-worked sand, gravel, and clay, and of swamp or marsh deposits at the border of the spreading sea. The Dakota corresponds in character and origin to the basal sandy deposits of the Gulf series in the Gulf region. As defined in Kansas, however, the Dakota group includes sandstone and shale of late Early Cretaceous age.

FIG. 264.—A large concretion weathered out of the Dakota sandstone and standing on a pedestal of sandstone, Pawnee County, Kans. (*R. C. Moore, Kansas Geol. Survey.*)

Colorado Group.—The next division of the Upper Cretaceous beds in the Western Interior region consists of shale, chalky limestone, and in places of sandstone. The strata, almost entirely marine, are called the Colorado group. The lower part is composed mainly of dark clayey shale (Benton), 200 to 1,000 feet or more in thickness. It is extremely widespread, being known throughout practically all of this region, and it is remarkably uniform in character. In the country east of the Rocky Mountains there is a persistent, thinly and very evenly bedded limestone (Greenhorn) in the middle portion of the shale, and one of its beds, known as the fence-post limestone, furnishes large numbers of fence posts in the treeless prairies adjacent to the outcrop of the limestone,

In Wyoming the shale contains beds of sandstone that yield commercial quantities of oil and gas.

The upper part of the Colorado group east of the Rockies is made up of chalk and chalky shale (Niobrara), several hundred feet thick, which corresponds to the main chalk formation of the Gulf region, but in the west there are thick beds of dark clayey shale and sandstone instead of the chalk. The western Kansas chalk deposits are world-famous because of well-preserved remains of marine reptiles, fishes, birds, and flying reptiles that have been found there.

Montana and Laramie Groups.—Above the Colorado group are strata consisting mostly of very uniform dark-colored clay shale, but there is much sandstone. In the plains country east of the Rockies, the shale

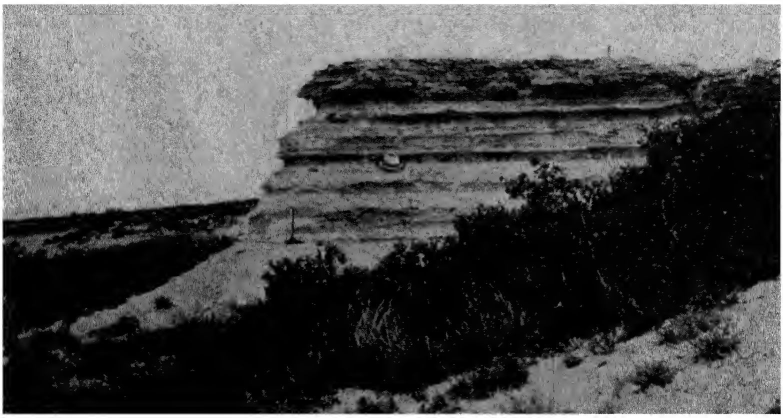

FIG. 265.—Outcrop of chalk (Niobrara) in Ellis County, western Kansas. (*N. W. Bass, Kansas Geol. Survey.*)

(Pierre) commonly attains a thickness of more than 2,000 feet, and locally, in the Colorado High Plains and along the northern Front Range, it is 7,000 or even 10,000 feet thick. The shale is overlaid by a persistent sandstone (Fox Hills). Physical characters, such as even bedding and widespread uniformity, and the presence of marine fossils show that these deposits were formed in the sea. Farther west, however, there are considerable thicknesses of land-laid sediments, some of which contain coal beds. In the region bordering the Rocky Mountains, the marine beds are followed conformably by nonmarine coal-bearing strata (Laramie and equivalent formations).

Conditions of Sedimentation.—Study of the Cretaceous rocks in the Western Interior region has shown that, although some parts are very uniform, there are others in which different sorts of sediments were deposited contemporaneously in near-by areas. For example, while dark marine shale was accumulating in one place, the rocks being formed elsewhere not far distant consist of (*a*) marine sandstone, (*b*) brackish-

water sandstone and shale, and (*c*) fresh-water sandstone, shale, and coal beds. Traced laterally, one type of deposit is found to grade into another; a very prominent sandstone becomes thinner and thinner in certain directions, eventually pinching out, as shale of equivalent age takes its place. Thus, the relations of different kinds of deposits are complex and many local formation names are employed. A clear demonstration of the interfingering and intergradation of shale and sandstone of marine, brackish-water, and fresh-water origin is seen in the Wasatch Plateau and Book Cliffs escarpment, which affords a continuous line of completely exposed Cretaceous strata extending more than 100 miles in Utah and Colorado. Sandstone, largely nonmarine and in part coal-bearing, predominates westward and passes laterally into marine shale eastward. In the southwestern exposures there are a few hundred feet of early Late Cretaceous marine shale at the base of these cliffs, overlaid by thick sandstone and shale, mainly of continental origin, representing the middle and later parts of the epoch. Northeastward, the top of the marine shale belongs to younger and younger horizons in the series, the sandstone facies being correspondingly reduced in thickness and representing only the latest part of the Cretaceous. Thus, evidence is presented to show that marine shale deposition extended much farther southwestward in this region in early Late Cretaceous time than later, that this type of sedimentation persisted without interruption until latest Cretaceous time in the northeastern part of the area considered, and that there was a gradual encroachment of land-laid sandy deposits upon marine shaly deposits during the epoch. The sea border was pushed slowly and intermittently eastward. Finally, marine deposits practically disappear, possibly owing to a gradual withdrawal of the sea on account of uplift of the continent, but undoubtedly owing in part to filling of the geosynclinal basin by sediments.

Pacific Border Region

In California, Oregon, Washington, British Columbia, and Alaska there are thick deposits of Cretaceous age representing both the Lower and Upper divisions, but the sea in which the marine strata of this region were formed appears not to have been connected directly with that of the Western Interior. The fossils show Asiatic affinities or, rather, they belong to what may be termed a circum-Pacific fauna. Sandstones and sandy shales predominate, but locally there are conglomerates and there are a few thin limestones. The nonmarine beds are coal-bearing in part. Volcanic rocks, consisting of lavas, tuffs, and ash beds, are prominent in places, especially in western British Columbia. The thickness of the Cretaceous rocks in the Pacific Border area exceeds 3,000 feet in most places, and in northern California it attains a total of nearly 30,000 feet, of which more than 26,000 feet is referred to the Shastan series

(Knoxville and Horsetown beds) of Early Cretaceous age, and 3,900 feet to the Chico series of Late Cretaceous age. The great thickness and the predominance of sandstone and shale support the conclusion that sedimentation was rapid. The enormous quantities of land waste appear to have been derived mainly from elevated country to the east that had been affected by mountain-making movements at the close of Jurassic time, but the geosyncline was also bordered on much of the west by land. The unconformity at the base of the Cretaceous in the Pacific region is generally prominent, for the older rocks were much folded, and even metamorphosed, and then eroded before the beginning of Lower Cretaceous deposition. The Cretaceous rocks have been much disturbed subsequently in most places.

CRETACEOUS FORMATIONS OF OTHER CONTINENTS

Cretaceous rocks are found in all of the continents. Both marine and nonmarine deposits occur, the greater spread of the sea being recorded generally in the later (Upper Cretaceous) part of the period.

Europe.—The European Cretaceous rocks are especially important to students because of the classic researches on the nature of the deposits and their contained fossils, and because these rocks in Europe are the standard of comparison, the type section, for other parts of the world. The deposits are commonly divided into two series, called Lower Cretaceous and Upper Cretaceous, respectively, and each is made up of several named groups of beds (see table, page 433). The Lower Cretaceous marine beds are mainly restricted to the south central part of the continent, chiefly in France, Switzerland, and southern Germany, but marine deposits also occur in northern Russia. These strata are mostly very fossiliferous. Continental deposits of equivalent age occur in northern Europe, including especially parts of England, northern Germany, and Russia.

In the Upper Cretaceous, marine strata are much more widespread. As already noted, chalk is prominent in this part of the system in England and France, but it is not an important type of deposit elsewhere. The chalk is regularly bedded and several hundred feet thick. Some of it is made up almost wholly of microscopic shells of Foraminifera that accumulated in the quiet clear waters of this region in almost incredible numbers, but other parts are clayey and impure. Nodules of dark flint are common. Many of the beds contain numerous invertebrate fossils besides the Foraminifera.

Africa.—Cretaceous rocks are well-known in the Mediterranean region, including parts of northern Africa, and they also extend into the Sahara, where much of the desert sand is derived from breaking down of Cretaceous sandstone. Rocks of this age occur also in southeastern Africa, Madagascar, the Cape Colony, and on the west coast.

Asia.—Lower Cretaceous deposits are found in the trough which formerly extended eastward from the Mediterranean far across Asia, but the Upper Cretaceous is very much more widespread, being known not only in the western and central parts of the continent but in southern India, northern Siberia, Japan, and the East Indies.

Australia was widely covered by the Cretaceous sea, about one-third of the continent having been submerged.

South America is known to have both marine and nonmarine beds of Early and Late Cretaceous age. The chief region of their development is along the Andean geosyncline, now a lofty mountain belt, from Colombia to the Straits of Magellan. There are also extensive deposits of Cretaceous rocks in the Amazon Valley.

PHYSICAL HISTORY OF CRETACEOUS TIME

The history of the Cretaceous period may be considered conveniently in sections devoted respectively to (1) erosion of the land, (2) continental and marine sedimentation, (3) mountain disturbances at the close of the period, (4) igneous activity, and (5) climate. The interesting record of life development during Cretaceous time is considered in a following chapter.

Erosion of the Land

During Cretaceous time, large parts of the continent were being eroded. Some areas appear to have been subjected to erosion almost continuously in the preceding parts of the Mesozoic era. Under such conditions and lacking pronounced upwarp of the land surface, the probability of extensive peneplanation is strong. In regions of flat-lying strata it may be difficult to differentiate horizontal land surfaces due to prolonged denudation from those that are dependent on rock structure. However, a plain that bevels smoothly folded and faulted rocks of varying hardness, or that cuts evenly across massive crystalline rocks, is strongly indicative of planation by erosion. Under certain conditions, wave action in a transgressing sea may accomplish such planation but erosion of this sort is commonly restricted to coastal belts and is identifiable by its association with marine deposits, and by other characters. Peneplanation due to stream erosion is generally characterized by the shape and size of the area affected, by imperfections in reduction of the land to a plane surface, by possible presence of stream-borne materials and absence of marine sediments on the erosion plane. On the other hand, it is possible, of course, that a stream-formed peneplain may be submerged and flooded by the sea, which smoothes irregularities by wave action and covers all with a mantle of marine deposits.

The Appalachian Region.—Almost all of North America that was not covered by the Cretaceous sea was probably eroded to a lowland by the latter part of Cretaceous time. Evidence of peneplanation is most distinct in the Appalachian Mountain district of the eastern United States. Here the many mountain ridges formed by upturned resistant formations and uplands formed by hard crystalline rocks have accordant, smoothly beveled summits. This feature defines an erosion surface (Schooley peneplain) that required a long time to produce, for in most places even the hardest rocks were planed down to a nearly level surface. The coastal belt, at least, had been fairly well smoothed before the beginning of deposition of the Lower Cretaceous formations, for there is not much unevenness of the floor (Fall Zone peneplain) on which these beds rest. Deposition of the Cretaceous sediments was accompanied by further erosion of the land, and, judging by the slight chemical decomposition

of much of the sediments, erosion was active. By the latter part of Cretaceous time the former mountains adjacent to the coastal plain had been obliterated; the country was a featureless lowland on which streams flowed across the edges of tilted beds without regard to structure or hardness of the rocks. Subsequent uplift of the Appalachian region has caused streams to excavate the softer materials, leaving the horizontally planed hard-rock formations to mark the old peneplain. Since the elevation of the peneplain has amounted in places to more than 3,000 feet, the relief due to stream carving is of mountainous scale. The present mountains are thus the result of stream work that during Cenozoic time has dissected the upwarped Schooley peneplain.

FIG. 266.—Alcove in Mesaverde sandstone with habitations of cliff dwellers. Mesa Verde National Park, southwestern Colorado. (*U. S. Geol. Survey.*)

It is possible, as recently suggested (D. W. Johnson), that Cretaceous coastal plains sediments, resting on a pre-Cretaceous (Fall Zone) peneplain, may have once covered a large part of the Appalachian area, extending inland very much farther than now, and that main drainage lines established on the plain were superposed on the underlying folded and beveled rocks when regional uplift caused renewed erosion. In this case, the development of the Schooley peneplain must be assigned mainly to post-Cretaceous erosion. All things considered, it seems probable that the Schooley peneplain was eroded during the early part of the Tertiary period, rather than in the Cretaceous and preceding Mesozoic time as has been commonly supposed (see Figs. 332).

Erosion in Other Regions.—The central and northern parts of North America which contain no Cretaceous deposits were presumably land at this time and were subject to erosion. Peneplains are recognized in parts of the area but are not certainly identified as having been formed in the Cretaceous period. The Mississippi Valley was probably peneplaned. The nearly flat-lying rocks actually have a slight dip and are

beveled by erosion that has cut across the edges of formations in a nearly horizontal plane. Unlike the Appalachian area, the interior of the continent shows no evidence of having been greatly elevated at any time.

The region west of the great Upper Cretaceous seaway in the Western Interior, that is, Nevada, eastern California, and areas northward, must have been very deeply eroded in the latter part of Mesozoic time. Mountain-making disturbances had occurred here at the close of the Jurassic period (Jurasside orogeny), and it is probable that further uplifts took place during the Cretaceous. Evidence of the extensive erosion predicated is found in the thickness and increasing coarseness of Cretaceous rocks in the Western Interior geosyncline westward, and in the California trough eastward. This land between the two belts of sedimentation was certainly the source of a large part of the detritus that went to make the western Cretaceous formations.

Continental and Marine Sedimentation

The distribution and chief characters of the Cretaceous deposits in North America have been described. Interpreting this record, we may arrange in consecutive order the history of continental and marine sedimentation during the period.

Early Cretaceous Epoch.—The earliest marine invasion of the North American continent took place in Mexico, for the oldest sea-laid rocks of the period are found there. Gradually the Texas and Louisiana region was submerged (Trinity stage), the initial deposits consisting of sand and gravel derived from the weathered older rocks. The succeeding beds, mostly limestone, indicate clear water and show that the region adjacent to the Gulf was not far above sea level, for otherwise quantities of mud and sand should have been contributed to the sea. Progressive thinning of the early Comanche sediments northward accords with the longer occupation of the southern areas in comparison with the northern. Temporary partial retreat of the sea brought to a close the first stage of Early Cretaceous history in the Gulf region, and a readvance that exceeded the earlier maximum submergence introduced the second stage (Fredericksburg). This was also characterized mainly by clear waters and deposition of calcium carbonate, the beds being thicker in the south than in the north. The marginal deposits of the sea of this time, as seen in southern Kansas, consist mostly of sand and silty clay. The third stage (Washita) witnessed minor geographic changes and certain differences in the nature of the marine deposits and organisms. The beds are mostly calcareous, however. Retreat of the sea, upwarping of northwestern Louisiana, and erosion brought the Early Cretaceous epoch to a close.

While the sea was flooding parts of the Gulf region, stream and swamp deposits were being formed along the Atlantic Border in what is now the

Coastal Plain, and in parts of the Western Interior. In the east, these deposits are not very thick; they contain a few thin, unimportant coal beds. In the west, however, Lower Cretaceous nonmarine rocks are locally measured in thousands of feet and there are numerous workable coal beds of great extent. Swamps with abundant plants persisted for a long time and coal-forming conditions were recurrent in this region.

The Pacific Border shows the greatest known thickness of Lower Cretaceous sedimentary rocks on the continent. A relatively narrow sea-filled trough on the west side of the mountains that were formed at the close of Jurassic time received huge quantities of gravel, sand, and silt that were carried into it by streams. As sedimentation proceeded, the trough sank deeper and deeper.

Late Cretaceous Epoch.—In Late Cretaceous time the sea not only reoccupied territory that was temporarily uncovered at the close of

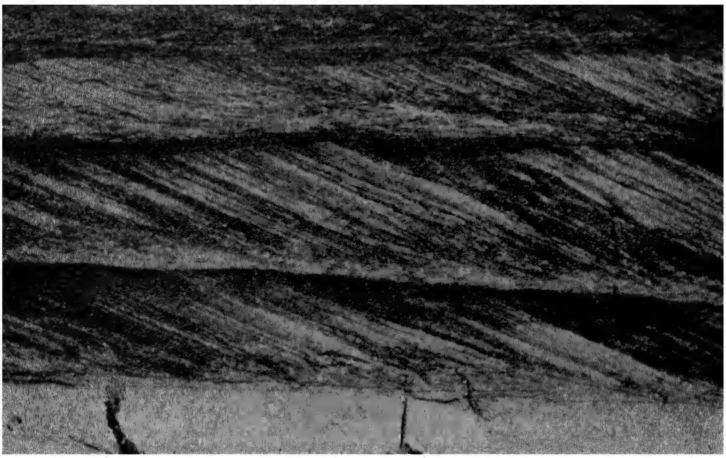

FIG. 267.—Cross-bedding in the Dakota sandstone. This type of cross-bedding which is fairly uniform in the direction of dip indicates deposition by running water. Near Bennett, Nebr. (*N. H. Darton, U. S. Geol. Survey.*)

the preceding epoch but extended rapidly far beyond the shores of the greatest Early Cretaceous sea. This really enormous flooding in the Gulf and Western Interior country reached to the Arctic, forming a north-south mediterranean sea that was more than 1,500 miles wide in places. The submerged region was evidently a sand- and soil-covered lowland plain before depression of the land or rise of sea level caused the waters to advance so widely and, in a geologic sense, so quickly. The sandy materials of this land were reworked by the sea to form a basal sandstone (Dakota), part of which, however, is nonmarine. The succeeding dark-colored marine shale, limestone, chalk, and in places sandstone are noteworthy because of very wide distribution and general uniformity. The western portion of the sea was gradually displaced by brackish- and

fresh-water deposits containing important coal beds, and eventually coal-forming conditions existed far to the east (Laramie of eastern Colorado). The sediments of this basin appear to have been derived mainly from the west, as shown by increasing thickness and coarseness and proportion of land deposits westward.

The most prominent sort of deposit of Late Cretaceous age in the Gulf region is chalk and chalky shale, which indicates sedimentation in clearer waters farther from the sources of supply of land waste. Also, as we might expect, the record is composed almost exclusively of marine beds. The eastern part of the Gulf region, which was apparently not covered by Lower Cretaceous deposits, was invaded by the Late Cretaceous sea, chalky beds being formed in parts of the area, while sand and shale were deposited in others. There are also thick nonmarine deposits.

The Atlantic Border contains Upper Cretaceous formations, showing that fluviatile sedimentation of sand, clay, and some gravel occurred in the early part of the epoch, and then there is a hiatus until late in the period when the sea advanced over the coastal belt.

The deeply subsiding trough in the California region and northward, which received such great thicknesses of Lower Cretaceous sediments, continued mostly to be covered by the sea, but the volume of Upper Cretaceous rocks is much smaller. The formations consist almost wholly of land detritus carried into the sea from uplands to the east; in places there is much volcanic material deposited with the products of erosion.

Close of the Period

The Laramie Problem.—Viewed broadly, the Cretaceous and its fossils are very different from the Tertiary and its contained remains of life. The close of Cretaceous time not only marks the end of a geologic period but, according to uniformly accepted definition, it terminates a geologic era. The essential reasons for reckoning this as a major punctuation point in earth history are (1) the unusually profound crustal movements which occurred at this time, making great mountain systems and introducing geographic changes of far-reaching importance, and (2) the very striking, relatively sudden changes in the nature of living organisms which were doubtless dependent in large part on the altered physical environments.

Uplift of the continents accompanied by withdrawal of the sea should be marked, we may suppose, by interruption of sedimentation and by erosion of previously deposited beds, making unconformities, and the boundary between rocks of the Cretaceous and Tertiary systems should be clearly defined. This is the case in many places. Folded or tilted Cretaceous and older rocks are seen beveled by erosion and overlaid by Early Tertiary strata. Elsewhere, undisturbed Cretaceous beds are

delimited at the top by a distinct erosional unconformity, or by a hiatus in sedimentation that is marked by changes in lithology and especially by sudden disappearance of old species of organisms and introduction of new ones. In the latter cases, the Cretaceous and Tertiary strata may be parallel, but the division between them is readily established.

With these things in mind, it perhaps seems strange that in the Western Interior of North America there is a widespread group of beds, measuring in places some thousands of feet in thickness, that is not definitely classified as Cretaceous or Tertiary. In a sense these are transition beds. It is always to be remembered that time is continuous and that the divisions of it established by man are somewhat arbitrary.

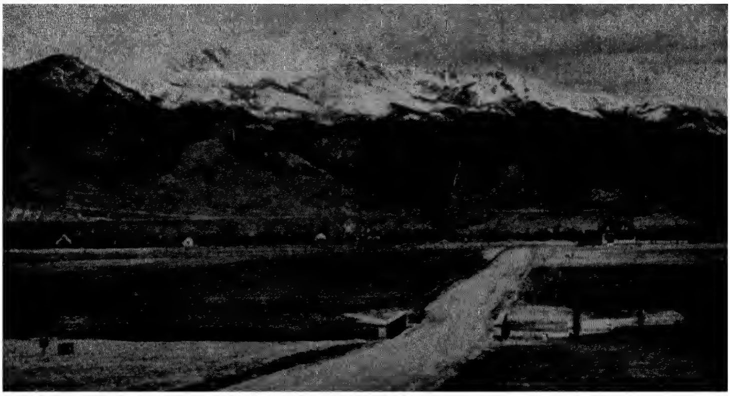

FIG. 268.—The Front Range of the Rocky Mountains, looking west from a point near Colorado Springs, Colo. The snow-covered summit of Pikes Peak appears in the central background. The Rockies were elevated at the beginning of the Cenozoic era, sedimentary formations being steeply upturned and faulted. The mountains were subsequently peneplaned and then reelevated two or more times by vertical movements that did not involve folding of sedimentary rocks. The last uplift occurred in Late Cenozoic time. (*U. S. Geol. Survey.*)

Continuity of sedimentation during intersystemic and even interera "breaks" is to be expected in certain places and conditions. In the Western Interior region, the beginning of mountain-making movements in Late Cretaceous time, along with the gradual filling of the broad epicontinental sea by sediments that had taken place, caused the nearly complete retreat of the inland salt waters. Continental sedimentation, mostly by streams but in part by winds and by lakes and swamps, became very extensive, rock debris being supplied by erosion of the locally uplifted areas. These subaerial deposits, a large part of which have escaped destruction by subsequent erosion, partly bridge the gap between undoubted Cretaceous and definitely identified Tertiary formations. Some of the transition beds (Lance and equivalents) contain remains of land reptiles (especially dinosaurs) that are closely related to characteristic animals of the Cretaceous and that are entirely foreign to the Ter-

tiary. One formation (Cannonball) in North Dakota contains a marine invertebrate fauna which is most like the very late Cretaceous marine faunas. On the other hand, the abundant fossil plants appear to be distinctively Tertiary in aspect, and some formations contain numerous primitive types of mammals, the class of animals which became dominant in Tertiary and later time. Because the name Laramie was initially applied to this supposed transition zone, the problem of determining the exact age of the deposits and of fixing the boundary between Cretaceous and Tertiary in the Western Interior region has become known as the Laramie problem.

Formerly, it was supposed that a single epoch of crustal movement was involved in the folding of Cretaceous and older rocks of the Rocky Mountain region. If this were true, it should be possible to determine the age of the so-called transition beds with respect to this folding, and, defining the close of the Cretaceous as coincident with this deformation, it would then be possible to class the doubtful beds in one period or the other, despite transitional characters that are shown. As a matter of fact, studies have brought to light evidence indicating that several deformative movements of varying intensity, of different age, and affecting different areas unequally must be recognized near the close of the Mesozoic and beginning of the Cenozoic, but there is agreement that one of the disturbances (pre-Wasatch) is of chief importance. Which geologic datum shall be selected as the dividing point in the time scale? There is not yet agreement on this question, but it is more important to understand the true conditions and the history that is represented than to settle a matter of definition.

Following are some of the chief points to be considered in study of the Laramie problem. (1) Except as shown by marine sediments (Cannonball) in North Dakota, the sea that had covered the Western Interior of the continent during most of Late Cretaceous time disappeared after deposition of the widespread dark shale (Pierre) and sandstone (Fox Hills) that belong at the top of the undoubted Cretaceous. Nonmarine deposits (Laramie, Vermejo) in parts of the Rocky Mountain region are generally agreed to belong to the uppermost Cretaceous and may be contemporaneous with some of the marine deposits mentioned. (2) Slightly younger nonmarine formations (Raton, Dawson, Denver, Arapahoe, Lance), which may be classed as transition beds, have been reported to be separated from underlying rocks by a major unconformity which is interpreted to signify a mountain-making uplift. Accordingly, this unconformity has been suggested as a logical boundary between Cretaceous and Tertiary. Recent studies (Reeside, Dobbin, Lovering) have shown, however, that the break at this point, where recognizable at all, is of minor importance, and that there is certainly no indication of mountain-building on a large scale. (3) Similarly, there is absence of a major unconformity between these "transition beds" and the next overlying formations (Fort Union, Puerco, Torrejon) that are commonly classed as oldest Tertiary. (4) That geographic changes of much importance were in progress at about this time is indicated by the profound alteration in the life of the lands. The beginning of this rapid change appears in the lowermost transition beds (Lance and equivalents), even though these contain characteristic land animals and marine

invertebrates of Mesozoic aspect. Modification of fauna and flora in the direction of typical Tertiary characters has advanced so far in the next younger beds (Fort Union and equivalents) that these have long been accepted as belonging definitely to the Tertiary. (5) The most widespread, strongly marked physical evidence of change, involving the folding, faulting, and truncation by erosion of great thicknesses of beds, is geologically dated as pre-Wasatch, which is slightly younger than Fort Union.

The apparent continuity of deposition in the western plains does not necessarily mean that mountain-making in adjacent territory was lacking. It signifies rather that sedimentation in the particular places where the transition beds now occur was little interrupted. Materials recognizable as having been derived from Paleozoic rocks and granitic debris that probably came from erosion of pre-Cambrian rocks are found in undoubted late Upper Cretaceous formations (Laramie, Kaiparowits). They occur in larger proportions in some cases in the transition beds (for example, Dawson arkose). This means that the old rocks from which the sediments were obtained were exposed to erosion and implies a beginning in Late Cretaceous time of the crustal disturbances that culminated later. The pre-Wasatch orogeny indicates either that important mountain-making movements occurred after the beginning of Tertiary time, or, if this is defined as marking the boundary between the Cretaceous and Tertiary, that the main biologic change which distinguishes the eras occurred in Late Mesozoic time. It is known that profound crustal disturbances continued a long time after the Wasatch. For the present it seems best to draw the boundary line marking the close of the Cretaceous mainly on paleontologic grounds, placing it between the Lance transition beds and the Fort Union. This conforms with common practice, although the United States Geological Survey classes Lance as Tertiary(?).

Mountain-building.—The mountain-building near the close of Cretaceous time is evidenced by steeply tilted and folded Cretaceous strata, by great thrust faults that dislocate Cretaceous formations, and by the occurrence of Early Tertiary beds (Wasatch), adjacent to or overlying the deformed older rocks, that are unaffected by the forces that compressed and upheaved the pre-Tertiary rocks. Hard beds in the upturned Cretaceous strata make hogback ridges, as well shown by Sky-line Drive ridge at Cañon City, Colo., and many others. Thrust-faulting is especially prominent in western Montana, Idaho, Wyoming, and Utah. Some of the faults are determined as Late Cretaceous or pre-Tertiary in age, whereas others belong definitely to the Tertiary.

The post-Cretaceous mountain-building is called the Rocky Mountain (or Laramide) revolution, because a great chain of mountains was formed in the belt now occupied by the Rockies. The mountains of the present day in this region are not those made by folding and thrusting at the end of the Cretaceous period, for the latter, though probably once as imposing and lofty as their modern successors, became worn down to a nearly smooth plain in mid-Tertiary time. The mountainous topography seen in this belt today is of very recent geologic origin. It is the result of vertical upwarping in Late Tertiary and Quaternary time that rejuvenated the streams, provided conditions favorable for mountain glaciation, and otherwise produced the ruggedness that has been carved

in the peneplaned roots of the ancient mountains. This recent rebirth of the Rockies was not the result of compressive stresses that folded and thrust-faulted the rock strata; it was simply a bodily upward movement. On the other hand, the folded and faulted structure of the Rocky Moun-

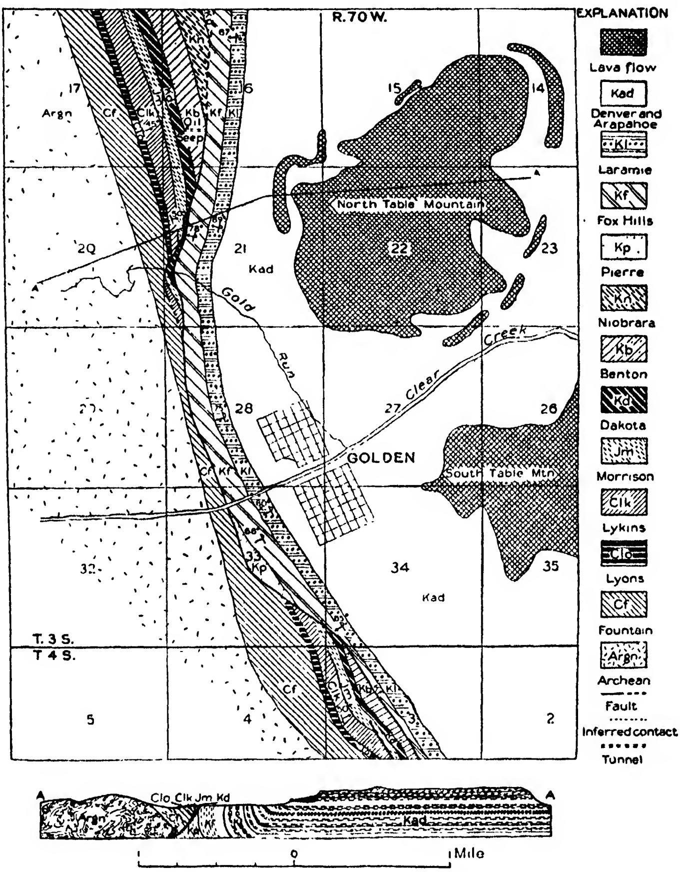

FIG. 269.—Geologic map and section of area near Golden, Colo. (a short distance west of Denver), showing upturned Cretaceous and older rocks at the margin of the Rocky Mountains. (*U. S. Geol. Survey.*)

tain Front and of other parts of the chain (except locally) are due to the orogeny that closed the Mesozoic (see Fig. 360, page 580).

It is perhaps well to call attention here to a common, thoughtless misconception that the granite core of a mountain range like the Rockies is *intruded* into the mountains. Volcanic activity is generally associated with mountain-building, and granitic or other igneous magmas may invade parts of the rock masses that are involved in an orogenic movement. But all such intrusions intersect the previously existing rocks and are regarded as younger than them. Excepting some places where relatively late magmatic invasions have occurred, the granites of the Rockies are all older than the Cambrian which rests unconformably upon them (Fig. 52) and enormously older

than the end of the Cretaceous when mountain uplift occurred. The formation of the mountains was accomplished by deformation of solid rocks, both those of sedimentary and those of igneous origin. The slow distortion and bending of huge masses of solid crystalline rock like granite, under influence of irresistible squeezing, are concepts difficult to grasp, yet deformation of this sort is commonly evidenced in geology.

The Rocky Mountain revolution is represented in South America by folding and faulting of the eastern Andes. These movements produced a great range of mountains, but, as in the case of the Rockies, the modern Andes are of much more recent origin. There was mountain-building at this time also in Antarctica, the West Indies, and northeastern Asia. Other lands were subjected to gentle uplift and warping but not intensive folding. The mountain-making activities of this time thus appear to be of Pacific origin.

Warping Movements.—Elevation of the peneplaned Appalachian Mountain region (Fall Zone peneplain overlaid by Cretaceous sediments?), accompanied by warping, occurred at about the close of Cretaceous time and the streams began to cut downward more rapidly again, carrying the eroded materials seaward to build the Early Tertiary deposits. Gentle uplift of this sort but smaller in amount probably affected the Mississippi Valley region. The structural attitude of the Great Plains country was also given essentially its present form, the Cretaceous and older rocks being beveled by erosion before mid-Tertiary time.

Igneous Activity

Despite general stability of the earth crust in Cretaceous time, as indicated by the great spread of shallow seas, there is evidence of igneous activity in many places. One of the largest known outpourings of lava in geologic history is found in the Dekkan Plateau of southern India, and associated fossil-bearing land sediments show that the flows are of Late Cretaceous age. These lavas, mostly basalts, now cover an area of 200,000 square miles but it is estimated that their original area may have been half a million square miles. Near Bombay they are about 10,000 feet thick; eastward and southward they are much thinner. Individual flows have an average thickness of about 15 feet. Eastern Africa also contains vast accumulations of volcanic rocks apparently related in origin to faulting on a large scale that occurred late in the Cretaceous. Volcanic eruptions in Arabia belong mainly to the mid-portion of the period. The igneous activity of these regions bordering the Indian Ocean is thought to have genetic connection with the breaking-up and downward sinking of segments of the earth crust that had formed part of ancient Gondwanaland, these segments now forming part of the floor of the Indian Ocean.

North America also contains record of Cretaceous vulcanism on a large scale. Unlike the quiet-type lava flows of India, however, the

igneous materials of this continent are largely the product of explosive eruptions (volcanic ash, tuff fragments). These occur in many places in the water-laid sedimentary formations of Cretaceous age. In the Gulf region, volcanoes are known to have existed before the beginning of Gulfian sedimentation, and others appeared later in the Cretaceous. Some formations hundreds of feet thick and covering a large area are mainly composed of reworked igneous matter. Many volcanic necks have also been discovered. The distribution of the vents and of igneous intrusions is very suggestive, for there is rather definite alignment on one of the chief structural features of the Gulf plains country, a line of faulting and flexing that separates the downwarped coastal region from the relatively stable interior platform of the continent (Balcones fault zone).

The shale and chalk beds of the Upper Cretaceous in Texas, Kansas, and many parts of the Western Interior contain many thin beds of bentonite, a chemically altered volcanic ash. These beds are very helpful in correlating sections of the formations containing them, for each ash bed is a strictly contemporaneous deposit and beds less than an inch in thickness are known to extend uniformly over hundreds and perhaps thousands of square miles. The Upper Cretaceous of Colorado, Wyoming, and Montana has been found to contain very thick and extensive deposits of volcanic ash and other igneous matter (especially in the Livingston, Aspen, and Mowry formations).

Climate

Inferences concerning the climate of Cretaceous time are based mainly on the nature and distribution of land plants and on paleogeographic considerations. Palms, ferns, and especially the breadfruit tree (*Artocarpus*), all of which occur in the Cretaceous of western Greenland, and plants from Svalbard, within 11 degrees of the North Pole, are commonly cited as indicating subtropical climate. However, some paleobotanists (Berry) strongly doubt the significance of this testimony, pointing out that moisture conditions are more important than temperature, that plant groups show greater adaptative capacities in the advancing and peak stages of their evolutional career than in the decline (applies to cycad palms), and that for various reasons these and other deductions as to climate are insecure. It does seem clear, nevertheless, that distribution of warmth and moisture was much more uniform in the Cretaceous period than now. High latitudes may have been cool, but they were not frigid. There is no evidence of well-defined climatic zonation. The seas that extended across North America from Gulf to Arctic and across Eurasia were factors in making an equable climate, for large water bodies are natural regulators of moisture and temperature in the atmosphere,

and north-south circulation by currents must have differed considerably from present conditions. As previously noted, wide shallow seas and low lands without prominent mountain ranges promote uniformity of climate, while opposite conditions favor climatic differentiation. Physical characters of Cretaceous time approximate the former, present time the latter.

ECONOMIC PRODUCTS

The chief materials useful to man that are obtained from Cretaceous formations are coal, oil, gas, and water. In addition, these rocks yield building stone, materials for manufacture of Portland cement, clay for brick and tile and also for coarse and fine pottery, greensand (iron-potash hydrosilicate used as fertilizer), and diamonds (from Cretaceous igneous intrusions in Arkansas).

Coal of Cretaceous age occurs in the Western Interior region of the United States, western Canada, Alaska, Germany, Australia, New Zealand, and, less importantly, in many other places. The tonnage of workable coal is second only to that of Pennsylvanian age. The coal ranges in grade from lignite or brown coal with a relatively high moisture, ash, and volatile hydrocarbon content to anthracite, the latter occurring in a few places (as Colorado) where intrusion of igneous rocks or exceptional compression due to folding has metamorphosed the coal beds. A large part of the coal is bituminous or subbituminous.

Oil and gas are obtained from Cretaceous rocks chiefly in the Gulf and Rocky Mountain regions of North America. The main producing formations of the Gulf area are Comanchean limestones (Texas and Mexico), Gulfian sandstones (Texas, Louisiana, Arkansas), and pervious intrusive rock masses (Thrall and Lytton Springs, Texas). Some of the Mexican wells have yielded unusually large quantities of oil, one producing for a time at a rate exceeding 260,000 barrels a day. The Rocky Mountain fields are located in Wyoming, New Mexico, Montana, Colorado, and Alberta. The oil is of very good grade.

Cretaceous sandstones are an important source of fresh water in the Great Plains and Gulf regions of the United States and in Australia. In part, the flow of this water in deep wells is artesian. The most important formations are the Dakota and the Trinity.

SUMMARY

The Cretaceous system consists of widespread marine deposits of dark-colored shale, chalk, chalky limestone, and sandstone, and of extensive nonmarine deposits of shale, sandstone, and coal. In North America these formations are divisible into two series, Lower Cretaceous and Upper Cretaceous. Outcrops are found on the Atlantic Coastal Plain, in the Gulf of Mexico embayment, the Western Interior, and Pacific Border.

The Cretaceous of the *Atlantic region* occurs at the inner margin of the Coastal Plain, resting unconformably on older rocks and dipping gently seaward. It consists of Lower Cretaceous nonmarine sediments and of lower Upper Cretaceous nonmarine sands unconformably overlaid by Upper Cretaceous marine beds.

The western part of the *Gulf region* shows a nearly complete sequence of Cretaceous rocks, excepting the oldest and youngest European equivalents. It begins with oldest Comanchean (Lower Cretaceous) in Mexico and southwestern Texas and shows a progressive northward invasion of the sea across Texas and beyond. Three major divisions of the Comanchean rocks are recognized (Trinity, Fredericksburg, Washita). Each of these groups is thicker in the south and becomes thinner toward the north. Local uplift accompanied by erosion of Comanchean deposits and temporary retreat of the sea terminated Early Cretaceous time. The readvance of the sea in the Gulfian (Late Cretaceous) epoch was geologically rapid and extended far beyond the limit of Comanchean invasion, eventually joining with waters from the Arctic. The Gulf series consists of a basal sand, dark-colored shale, chalk, and chalky shale. The eastern part of the Gulf province appears to contain only Upper Cretaceous deposits which in part exhibit lateral gradation from sandy shale and sand to chalk; the lower part of the series consists of nonmarine sandy beds.

The *Western Interior region* shows the presence of nonmarine Lower Cretaceous deposits that are thick locally and contain workable coal beds. The rocks of Late Cretaceous age consist of a marine and nonmarine basal group (Dakota) in which sandstone is most prominent; a very extensive marine group (Colorado) made up of shale, chalk, and sandstone, but containing locally some continental beds; and at the top, of marine and nonmarine coal-bearing beds more equally divided (Montana, Laramie, and Lance). The extremely large area, considerable thickness, dominance of clastic sediments, and lateral gradation of marine and coal-bearing continental deposits are important characters in this province.

The *Pacific Border region* contains a rather narrow belt of exceedingly thick Cretaceous sediments representing both Early and Late Cretaceous time and indicating active erosion of an upland to the east while the geosynclinal area was steadily subsiding.

The *close of the period* was marked by diastrophic movements that define also the end of the Mesozoic era. The Rocky Mountains in North America and the Andes in South America were elevated as a great chain, but the present mountains in these regions are due wholly to later geologic movements. Deposition of continental sediments and some marine beds (North Dakota) continued in the Western Interior of the United States, forming *transition beds* that almost bridge the gap between Cretaceous and Tertiary. The determination of the proper boundary between these systems in the Western Interior is a difficult, long-controverted question that is known as the Laramie problem.

Vulcanism is evidenced by volcanic necks and other intrusions in the Gulf region, and by widespread layers of ash and water-laid tuffaceous

material derived from volcanic vents. The latter are thick and widespread in the Western Interior region. The region bordering the Indian Ocean, especially in India, was the scene of enormous outpouring of basaltic lava toward the close of Cretaceous time.

The *climate* of the period was generally mild.

Economic products obtained from Cretaceous rocks are important, including especially coal, oil, gas, and fresh water.

CHAPTER XXV

LIFE OF MESOZOIC TIME

MESOZOIC ANIMALS—THE AGE OF REPTILES AND AMMONITES

No part of earth history offers record of such strange and varied life as that of the so-called "mediaeval era" of life development. The culmination of the reptiles in size, specific differentiation, and numbers is accompanied by a very remarkable adaptation of members of this class to almost every type of environment and mode of life. Dinosaurs, the "terrible lizards," were the rulers of the land, attaining a ponderous bulk unequaled in history of land animals. Few, if any, predaceous creatures can rival the ferocious dagger-like teeth and claws of some of the carnivorous dinosaurs, and no armored, vertebrate animals of other type or time are more bizarre than some of the armored dinosaurs. Land reptiles of this time include also the true lizards, and in the waters of the land there were turtles and crocodiles. One group of reptiles developed a batlike form, becoming remarkably adapted for flight in the air. From reptiles, also, the birds were derived. Several different reptilian stocks became specially fitted for life in the sea. Some of them took on a striking fishlike form and became entirely unable to travel on land. The Mesozoic is well named the "Age of Reptiles."

Among invertebrates, also, there are many specially interesting organisms. The complexly sutured, mostly tight-coiled, and externally ornamented ammonoid cephalopods are undoubtedly the most distinctive and important. An almost incredible variety of these shells is represented by Mesozoic fossils, but none are known from younger rocks. As regards the evolution of invertebrate stocks, therefore, the era may be designated appropriately as the "Age of Ammonites." The appearance of very abundant cephalopods of the squid type is evidenced by innumerable cigar-shaped "guards" which form part of the internal shell structure. Pelecypods and gastropods increased greatly in importance and in similarity of form to modern types. Sea urchins were much more common and varied than at any earlier time.

Contrasting Features of Mesozoic and Paleozoic Life.—A general characteristic of the animals of Mesozoic time which may be emphasized is the contrast with Paleozoic life. So great is the change that early geologists were convinced that a world-wide catastrophe must have wiped out existing forms of life at the close of the Paleozoic era and that a new creation at the beginning of the Mesozoic had repeopled the earth

with different kinds of organisms. Generally speaking, the complexion of Mesozoic life is very unlike that of Paleozoic time. This is shown by (1) disappearance of such animals as the trilobites, blastoids, and archaic types of crinoids, bryozoans, and corals, (2) the great decline of such an abundant and characteristic Paleozoic group as the brachiopods, (3) the rapid development and differentiation of such groups as the ammonites among invertebrates, and the reptiles among vertebrates, and (4) the introduction of new types of organisms. Many of the Mesozoic classes of animals branched and expanded greatly during the era. The majority of these branches flourished for a time and then died, without seeing the beginning of Cenozoic time.

The changes in life at the close of the Paleozoic era are really not so profound as might be inferred from the statements just made, for all phyla, many orders, and not a few families and genera did survive from Permian into Triassic or later times. The Lower Triassic invertebrate

FIG. 270.—The long-tailed dinosaur *Diplodocus* which attained a length of 90 feet. (*Restoration by C. W. Gilmore, U. S. National Museum.*)

faunas include several forms that differ only in minor ways from Permian predecessors. Among vertebrates, also, there are Lower Triassic reptiles in both Europe and South Africa that are almost identical with Upper Permian species. A variety of new reptile types that are characteristic of Mesozoic time make appearance in the Upper Triassic rocks. In brief, while the contrast between Paleozoic and Mesozoic life is striking, present knowledge indicates plainly that the later faunas are descendants of the earlier ones and the two are not so sharply differentiated at the boundary of the eras as was once supposed.

The significant features of the animal life of the Mesozoic are advantageously studied according to zoologic divisions, but we shall take first the most striking group, the reptiles, next the other vertebrates, and finally, the invertebrates. The subdivisions of these are arranged approximately in order of relative importance rather than according to biologic order.

Reptiles

The dominance of reptiles is an outstanding character of life on the earth during the Mesozoic era. The progress of the reptiles, as of any

kind of life, may be measured (1) by numbers, variety, size, and similar physical characters, (2) by degree of success in getting food, in avoiding or conquering enemies, and otherwise in adaptation to environment, and (3) by the extent to which radiation into all possible modes of life is effected. In the Triassic, Jurassic, and Cretaceous periods, reptiles achieved the greatest abundance and variety of form and stature in their history. They learned to feed on many kinds of plants, fresh-water and marine invertebrates, fishes, amphibians, other reptiles, and doubtless some of the primitive mammals. The only real competitors were members of their own class. They became remarkably specialized for life on the lands, in the seas, and in the air.

Radiation of the Reptiles.—The first reptiles were sluggish animals that in form and general habits probably resembled their amphibian ancestors. As the reptilian stock developed, however, some of its branches became increasingly fitted in a variety of ways for life on the lands. Other branches returned to the waters and became specially adapted to the requirements of this mode of life. Still other branches took to the air and underwent some very radical changes of form. The plasticity and virility of the reptile group at this stage in its history are well shown by the rapid and wide radiation of these branches into practically all possible habitats. A similar tendency to expand remarkably and radiate widely is seen at a corresponding stage in the career of the mammals in Tertiary time, and to greater or less degree it appears in many other animal groups. This expansion and radiation are signs of racial adolescence, just as inadaptability to changing environment and over-specialized characters are marks of racial senescence.

Among *land reptiles* an important line of development appears in changes of the limbs that make for ease in carrying the weight of the body and for speed. Primitive reptiles, like their amphibian ancestors, carried the body close to the ground, the short, rather weak legs extending outward from the sides and then downward. The legs moved in a lateral arc, and in walking the gait was a slow, awkward waddle. The first improvement as regards locomotion on land is seen in a change of the attitude of the lower part of the limbs, bending downward so that the body of the reptile is somewhat elevated. This plan of the limbs is seen in modern lizards and very many Mesozoic land reptiles. A next and very important advance consists in swinging the entire length of the legs beneath the body, so that they move forward and backward in a vertical plane and considerably increase the length of the stride. Some of the Mesozoic reptiles, especially among the dinosaurs, show this development, but they do not carry it to the extreme seen in many of the mammals, where the length of limbs is increased by walking on the tips of the fingers and toes.

Aquatic reptiles show various degrees of adaptation to their environment as manifested by the form and structure of the limbs and by the shape of the body. The limbs tend to become paddle- or oarlike, the bones above the wrist and ankle becoming short and broad, while the phalanges are lengthened by additional joints. Such an organ is admirably fitted to serve in swimming but is quite useless for walking. Some of the aquatic reptiles developed a remarkable fishlike form, which is really the best design for swift movement in a fluid medium. They propelled themselves mainly or entirely by their tail which bore a good-sized fin, and there was a dorsal fin as well.

FIG. 271A.—The pickax-headed flying reptiles, *Pteranodon*, skeletons of which are found in the marine chalk of western Kansas.

The *flying reptiles* (and likewise the birds, which developed out of an entirely different reptile line) probably learned first to glide and only later to fly. Adaptation to flight through the air is seen in a general lightening of the bones of the skeleton, but especially by a very remarkable modification of the structure of the forelimbs, in the true flying reptiles for support of a membranous wing, and in the birds for a wing clothed with feathers.

This progressive radiation and modification of the reptile group into divergent branches with different modes of life and the consequent effects on body form and structure are outstanding features in the Mesozoic history of life. Let us now observe the chief characters of some of these branches.

Dinosaurs

The dinosaurs, or "terrible reptiles," may rightly be considered the dominant animals of Mesozoic time. Not only were they numerous and distributed over all of the continents but they developed a surprising diversity of form and size, and they became adapted to very different sorts of environment and modes of life. Dinosaurs include the largest, most ponderous land animals that are known. The maximum length was about 90 feet (*Diplodocus*), and the weight of the living animal in the case of the largest known forms (*Brachiosaurus*) probably exceeded

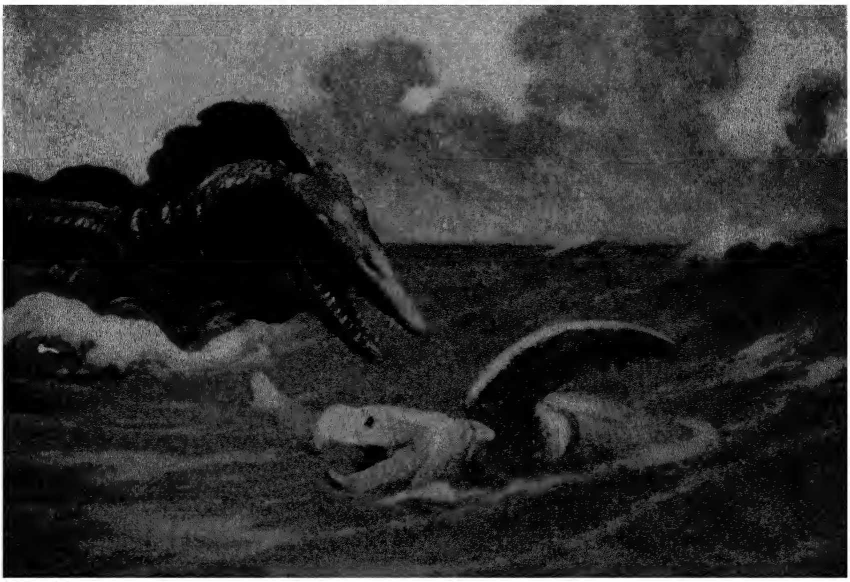

FIG. 271B.—One of the great mosasaurs, *Platecarpus*, and the turtle, *Archelon*, which lived in the Late Cretaceous seas of North America. (*C. R. Knight, Field Museum of Natural History.*)

80,000 pounds. Some of the carnivorous types might claim to be the most powerful and ferocious engines of destruction that have ever been produced in animate form, though low intelligence and lack of cunning may have made them actually less dangerous than many of the predaceous mammals. The armored and horned dinosaurs are very grotesque creatures, like the modern horned toad.

As to habits, there is evidence that some of the dinosaurs were swift-running creatures, others slow and lumbering; some splashed and waded about in shallow waters of the land, and a few were able to swim. The majority were plant eaters, but there were also fierce-looking flesh eaters. Not all of the dinosaurs were of huge size, for one Triassic type was not much larger than a small cat.

The first dinosaurs appeared in the Triassic period. They were very common in Jurassic and Early Cretaceous time and they declined and disappeared toward the close of the Mesozoic era.

Judged by characters of the skeleton, it is likely that the dinosaurs descended from two somewhat different ancestral reptile types, or at any rate there was an important divergence into two main lines which took place before the dinosaurs made their appearance, as far as represented by known fossils. One group, called Saurischia (hip bones reptile-like), shows affinities with the lizard-like reptiles. Here belong the giant quadrupedal herbivorous dinosaurs and the bipedal carnivores. The other group, called Ornithischia (hip bones birdlike), is related in several characters to the birds. All are herbivorous and there are three subgroups: bipedal (Ornithopoda), armored (Stegosauria), and horned (Ceratopsia). In describing these various types we may conveniently diverge somewhat from the scientific classification and take up first the carnivorous and then the herbivorous kinds.

The Carnivorous Dinosaurs.—Evidence of the predaceous, flesh-eating habits of this group of dinosaurs is clearly seen in the nature of the teeth and claw-armed limbs. The teeth were slightly curved, dagger-shaped, and sharply pointed. The long row of these on the upper and lower jaws of the wide-gaping mouth roughly interlock when the mouth is closed, forming a most fearsome and effective flesh-cutting, flesh-tearing apparatus. The claws were curved and talon-like. The hind limbs were large and powerful, while those in front were much smaller, in some absurdly small, useful only for grasping and holding prey, or not even for that. The part of the body in front of the walking limbs was more or less well counterbalanced by the rear part of the abdomen and a weighty tail. Some of these dinosaurs could certainly run swiftly but it is not likely that they were agile. The largest ones were so ponderous that the inertia of their lumbering charge against enemy or prey must have been all but irresistible. Their skin may have borne small scales but the body was not protected by armor.

Carnivorous dinosaurs are known in each of the Mesozoic periods. They show considerable range in size and in degree of specialization. We restrict mention here to two interesting representatives of the group, both of which are well-known from essentially complete skeletal remains.

Allosaurus is a carnivorous dinosaur of Late Jurassic (Morrison) age that lived in Wyoming, Colorado, and probably other parts of the North American continent. A mounted skeleton in the American Museum of Natural History, New York City, is 8 feet 3 inches in height and more than 34 feet in length. The large jaws are loosely hung and could evidently be opened widely, permitting the animal to swallow unusually large fragments of its prey or to gobble up smaller animals whole. The

teeth are recurved and powerful. The small front limbs and the large hind limbs are armed with strong curved claws.

The greatest of the carnivorous dinosaurs is *Tyrannosaurus*, two splendid specimens of which are mounted in the American Museum. Remains of this animal come from the latest Cretaceous rocks (Lance beds) in western North America. It reached a length of 47 feet and a height of approximately 20 feet. The head of one specimen is 4 feet 3 inches long, 3 feet 4 inches high, and nearly 3 feet wide. The sharp-edged teeth are 3 to 6 inches long and about 1 inch wide. The curved claws are 6 to 8 inches long. A truly awesome and terrifying thing this ancient

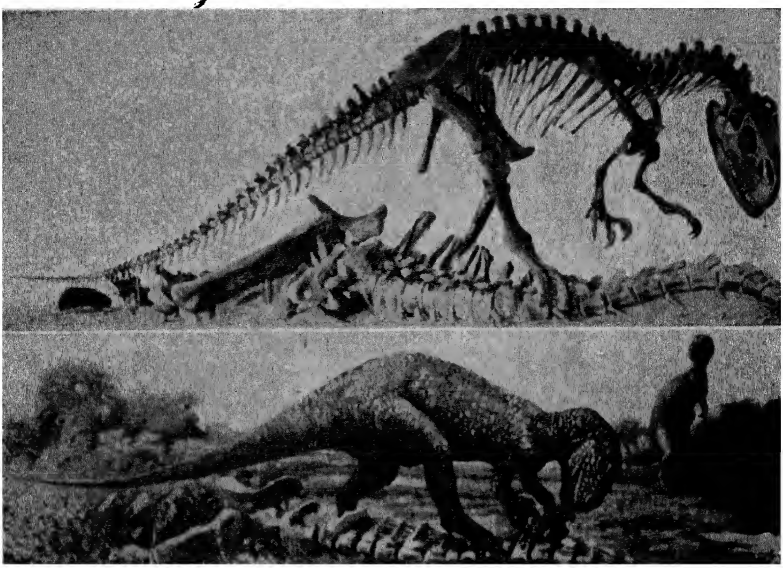

FIG. 272.—*Allosaurus*, a Late Jurassic carnivorous dinosaur of the western United States. The mounted skeleton and restoration represent the reptile feeding on the remains of a large herbivorous dinosaur. (*American Museum of Natural History*.)

beast must have been. It is interesting to note that the culmination of the flesh-eating reptiles was developed practically at the close of the reign of the dinosaurs and that with all others of this group it suddenly disappeared without trace.

The Herbivorous Dinosaurs.—The plant-feeding habit of most dinosaurs is indicated by the bluntly rounded or flattened ends or the leaf-shaped form of the teeth, which are not at all like the sharp flesh-cutting dental armament of the carnivores. All but one group of the herbivorous dinosaurs are quadrupedal and the toes are not provided with talons. Relatively short, pillar-like legs which are seen in these quadrupedal reptiles suggest a slow, lumbering gait. Such legs are necessary for support of the ponderous body and they serve adequately

for transportation from place to place in securing plant forage. These limbs are most unsuited for a beast of prey, however. A few swimming dinosaurs appear to have had webbed feet.

To the herbivore class belong much the greatest number, largest variety, and the hugest of the dinosaurs. Space permits us to notice briefly only a few of the main types. There are three groups of the

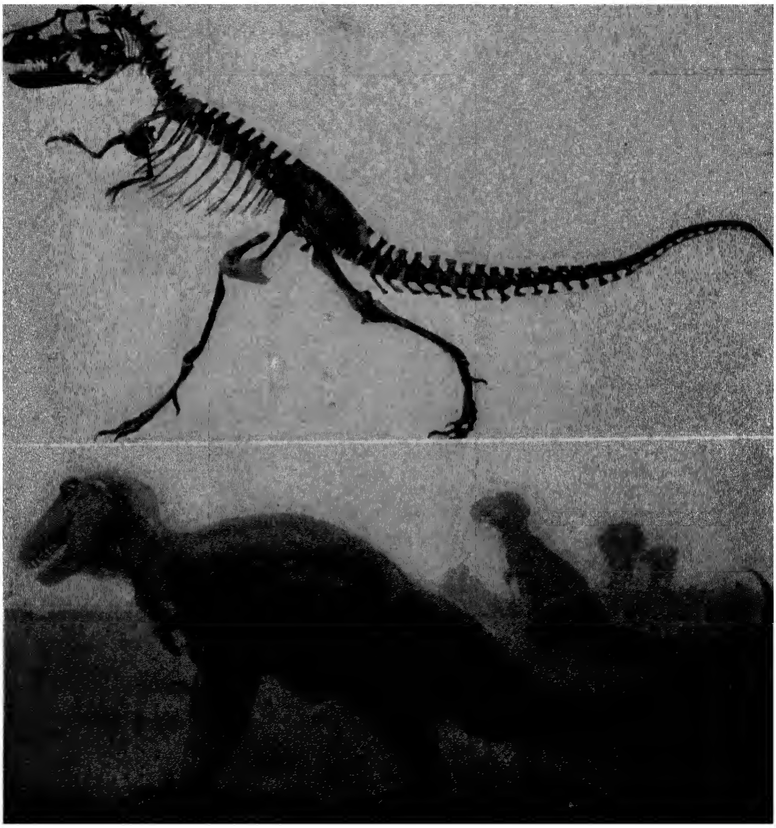

FIG. 273.—The greatest of the flesh-eating dinosaurs *Tyrannosaurus rex* ("king tyrant reptile"), which lived in Late Cretaceous time. (*Skeleton in American Museum of Natural History. Restoration by C. R. Knight, Field Museum of Natural History.*)

quadrupedal dinosaurs: (1) unarmored, (2) armored, and (3) horned; and one group of bipedal herbivorous dinosaurs.

The unarmored quadrupedal dinosaurs (*sauropods*) are well represented by *Brontosaurus* (Fig. 274), skeletal remains of which are found in several of the larger American museums. This animal had a length of approximately 70 feet and an estimated weight, in life, of about 38 tons. The head is surprisingly small, hardly as large as some of the single vertebrae, and the jaws are armed with a row of short, bluntly rounded

teeth. The neck is long and strong. The back arches over the body, rising highest at the hips which are massive and sturdily constructed. The tail is somewhat longer than the neck and tapering. The skeleton shows a wonderful adaptation for its functions, support of the body and movement in response to muscular action. The bones are trussed and thickened at points of stress but reduced where heavy bone would add to weight without increasing strength. Very massive limb bones, with rough ends that indicate joints formed largely of cartilage, are interpreted to mean an aquatic or semiaquatic life in which the huge weight, partly supported by water, did not cause the mechanical pressure at the joints

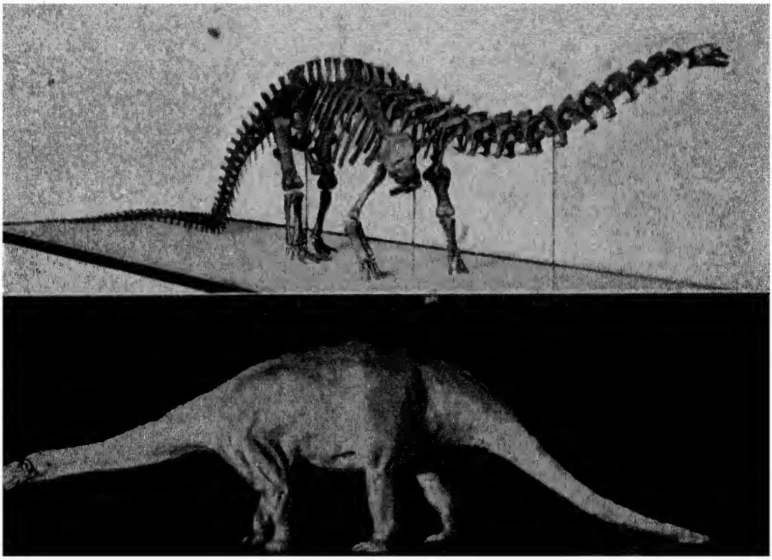

FIG. 274.—*Brontosaurus*, one of the largest of the dinosaurs, a quadrupedal herbivore. (*American Museum of Natural History.*)

that would exist in a dry-land animal. Dinosaurs of this general type are world-wide in distribution. They are best known from the Late Jurassic of North America and East Africa, and from the Cretaceous of the western United States, India, and Argentina. Some had a total length of nearly 90 feet. *Brachiosaurus* from East Africa probably exceeded the largest known *Brontosaurus* by two or three tons, live weight, and takes rank as the greatest known land animal.

Armored herbivorous dinosaurs (*stegosaurians*) made appearance in the Early Jurassic and, with much variety of size, form, and nature of the protecting bony armor, persisted to the Late Cretaceous. One of the best-known representatives of this group, though a grotesque and non-typical one, is *Stegosaurus* which lived in Colorado, Wyoming, and elsewhere in Late Jurassic (Morrison) time. This was a most awkward,

ungainly creature, some 20 feet long and 11 feet high, with strongly arched back, short neck and tail, and very small narrow head. The most striking features, however, are a double row of alternating broad bony plates that stood erect as a crest along the back, and on the tail two pairs of fearful spines, 2 feet or more in length. The plates along the back are roughly pear-shaped in outline, the largest ones, over the hips, being 2 feet high, 2½ feet long, and 4 inches thick at the base. Embedded in the skin are small bony plates. Less bizarre and much more perfect armament is seen in other dinosaurs of this class, as in *Ankylosaurus* of Late Cretaceous time. The head, body, tail, and limbs were so protected

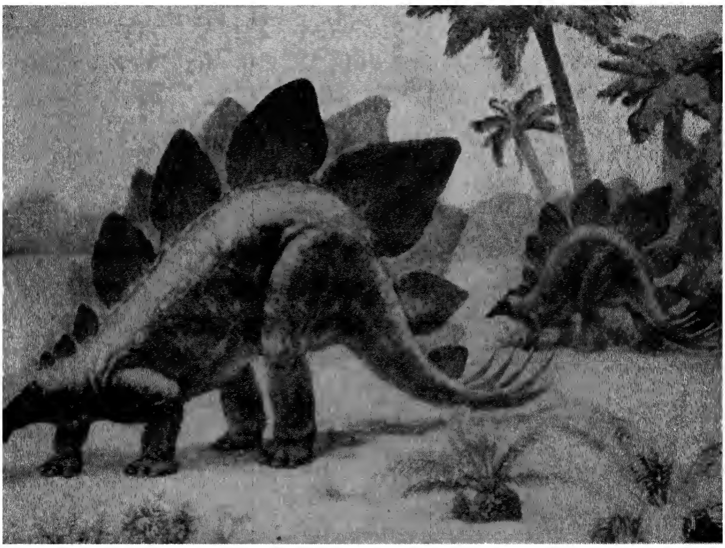

FIG. 275.—One of the strangest of the dinosaur line, the armored *Stegosaurus*, of Jurassic and Cretaceous age. (*C. R. Knight, Field Museum of Natural History.*)

by rows of thick bony plates that it must have been immune even from attacks of the tyrannosaur. Contemporary with the world's most powerful offensively armed animal we find one of nature's most impregnable defensively armed creatures.

The horned dinosaurs (*ceratopsians*) are a development of Late Cretaceous (Judith River to Lance) times in North America and eastern Asia. They are unknown in other periods or other continents. In strong contrast with other herbivorous dinosaurs, these had a relatively large head with a bony shield projecting backward so as partially to protect the neck and fore part of the body. The massive skull, measuring up to 8½ feet in length, carried one, two, or three strong, forward-projecting horns consisting of bone sheathed in horn. In some ceratopsians the horns were 3 or even 4 feet long. The front of the mouth was armed with a sharp cutting beak like that of a turtle. The body was stout and

barrel-shaped, the limbs moderately short and very strong, the tail short. The skeleton suggests tremendous prowess that was needed to withstand attacks of bulky, very powerful dinosaur enemies. It is clearly evident that the horns and defensive head shield were put to use by these dinosaurs, for fossils showing broken and healed horns, broken

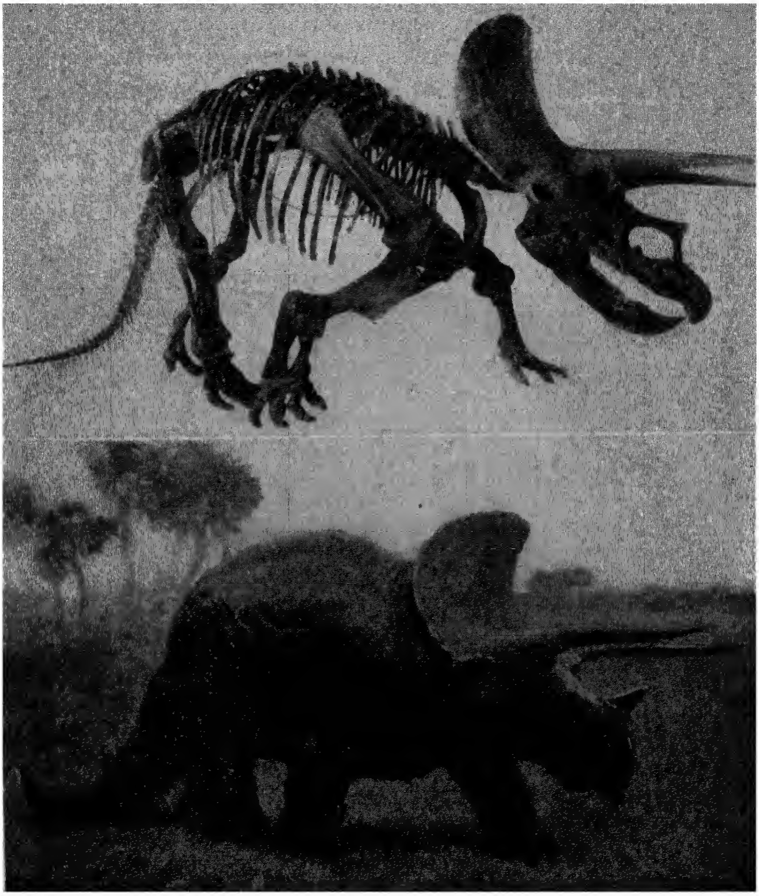

FIG. 276.—*Triceratops*, the three-horned late Cretaceous beaked dinosaur. (*Skeleton in the American Museum of Natural History. Restoration by C. R. Knight, Field Museum of Natural History.*)

jaws, and gouged and punctured shields are not unusual with these skulls. The horned dinosaurs were among the last survivors of their race.

Bipedal herbivorous dinosaurs (*ornithopods*) have very much the appearance of their carnivore cousins but differ greatly in the nature of the teeth. The front of the mouth was toothless, the muzzle terminating in a hard, horny beak, but the back of the mouth was solidly paved above and below by myriads of close-packed leaf-shaped teeth. They evidently formed a most efficient grinding apparatus that was probably used in

crushing the shells of mussels and the like grubbed up in streams and lakes as well as on plants. That these dinosaurs were at home in shallow waters is indicated by the laterally flattened shape of the tail, much like the alligator's tail, which serves as a sculling oar; also the front limbs, at least, appear to have been webbed. The three-toed hind limbs were large and powerful. In a few cases, portions of the skin as well as the bones of these dinosaurs have been preserved in the fossil state. There were thin scales and bony tubercles, but otherwise the body was unprotected. A remarkable "dinosaur mummy" with the skin nearly entire, drawn tightly over the bones is exhibited in the American Museum of Natural History (Fig. 83). Death overtook this animal in a desert area

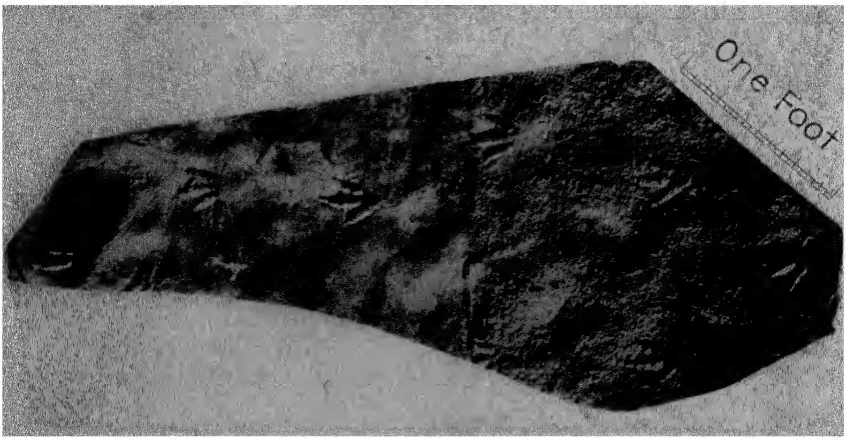

FIG. 277.—Dinosaur tracks on Upper Triassic sandstone, western Massachusetts. The smoothed part of the slab at the left was under water, the rough rain-pitted part at the right was above water. Amherst College collection. (*Photograph by Walter E. Corbin, Florence, Mass.*)

where dryness prevented rapid decay and drifting sand eventually buried the mummified remains.

Dinosaur Tracks.—In several parts of North America the well-preserved imprint of dinosaurs' feet are found in stratified rock, generally shaly sandstone, which was, of course, incoherent sediment when the tracks were made. Especially famous are places in the Connecticut River valley where flaggy sandstone slabs of Late Triassic age bear scores of clearly marked footprints that were made by different kinds and sizes of dinosaurs. Most of these tracks are three-toed, somewhat like those of a large bird, and when they were first discovered many years ago they were thought to have been made by birds. It is a strange fact that, although footprints are locally very abundant, actual remains of dinosaurs in the eastern Triassic rocks are extremely rare. There is no question, however, but that the tracks were made by dinosaurs. In some cases a known type of dinosaur can be identified by its track as well as by skeletal remains, but frequently the track is the only existing record of the species of dinosaur that made it. The tracks may be described and named scientifically as fossils.

Dinosaur Eggs.—Like most other reptiles it is probable that dinosaurs were hatched from eggs that were warmed by the heat of the sun. Indeed, a large number

of dinosaur eggs have been discovered by an expedition of the American Museum of Natural History in Mongolia and some have been found in America and Europe. These eggs are thin-shelled, elongate, and slightly less than a foot in length. The Mongolian eggs are those of a horned dinosaur (*Eoceratops*) of which specimens have been found showing practically every stage from newly hatched to adult. One Jurassic dinosaur skeleton is reported to contain an embryo within the abdomen, indicating that some of the dinosaurs, at least, were viviparous.

Intelligence of the Dinosaurs.—An interesting observation in connection with the study of dinosaur remains is the surprisingly small brain cavity in the skull. None of these reptiles appears to have had a brain that would weigh more than 2 pounds. Imagine a great land animal in which the brain constitutes but one forty-thousandth part! *Stegosaurus*, which was heavier than any elephant, had a 2½-ounce brain, about the same in size as that of a three-weeks-old kitten and less than one-fiftieth of the average elephant brain. Moreover, as pointed out by Lull, the cerebrum, which is the seat of the intellect, was only a minor part of the small dinosaur brain. The nerve centers in the spinal cord of the hip region were very much larger than the brain. All of this points clearly to an extremely low order of intelligence but a well-developed

FIG. 278.—A nest of 13 dinosaur eggs, as discovered in rock matrix in Mongolia. (*American Museum of Natural History.*)

nerve reflex control for movement of the great muscles. The dinosaur was a ponderous organic machine that responded mechanically to the stimuli of self-preservation and sex.

Extinction of Dinosaurs.—The career of the dinosaurs resembles that of many other kinds of life, a long period of development and differentiation, temporary dominance, then dramatically swift disappearance. Dinosaurs lived throughout Mesozoic time but none are known from rocks of Tertiary age, unless certain dinosaur-bearing deposits of the Rocky Mountain region are finally shown to belong to the basal Tertiary rather than uppermost Cretaceous. Causes of the extinction of these animals are conjectural. It has been suggested that the geographic and climatic changes at the close of the Mesozoic era so modified environment that the dinosaurs were unable to adapt themselves to the new conditions. The withdrawal of the great Cretaceous seas and uplift of lofty mountains undoubtedly brought about profound changes; but there had been similar, though lesser, changes during the life history of the dinosaur race. Moreover, there must have been plenty of country at the close of the Mesozoic era where physical environment congenial to dinosaurs persisted. It has been suggested that the rise of the primitive mammals, some of which may have learned to prey on the unguarded dinosaur eggs, is a possible factor in the disappearance of these monster reptiles. At all events the dinosaurs departed suddenly and a new chapter in the life record began.

Other Terrestrial Reptiles

Besides dinosaurs, there were many other reptiles of the land in the Mesozoic era. The Triassic rocks, especially in South Africa, have yielded many skeletons, among which are the theriodonts with mammal-like differentiation of the teeth; and large-tusked but otherwise toothless "anomodonts." Common in the Triassic of the western United States are several sorts of long- and narrow-snouted crocodilians, known as *phytosaurs*, which somewhat resemble the modern crocodiles and gavials. Turtles, lizards, and several other types occur, but snakes are not certainly known before the Cretaceous period. The most common reptiles of Early Mesozoic time were the thecodonts, which were small, active animals that tended to become bipedal. The thecodonts appear to be the ancestral stock from which the dinosaurs, flying reptiles, and birds are all derived.

Marine Reptiles

Not the least interesting of the strange reptiles that lived in Mesozoic times are the aquatic types. Possibly because of competition for food on

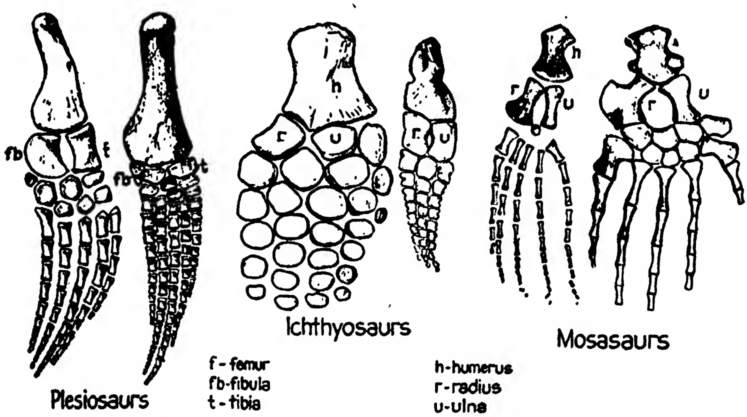

FIG. 279.—Drawing showing the limb structure of three types of aquatic reptiles. (*After Williston.*)

the land or because of enemies, or perhaps because food was easier to procure in the waters, some of the early reptiles were driven back to the sea from which their ancestors had emerged. They were handicapped by the necessity of breathing air and, at least initially, by the ill-adapted form of body and limbs for locomotion in a fluid medium, but this was partly offset by a superior mental capacity. There were at least four major reptile groups that invaded the Mesozoic seas and came to be very much at home in them. It is certainly significant that each of these different groups, though preserving individual peculiarities, shows the same type of structural modifications in becoming adapted to an aquatic environment; and this is true also of various mammals, like the whale and porpoise, that have taken to the sea. Let us note the character of these adaptations.

Rapid movement through water demands a body contour that is "streamlined" to give minimum resistance, and some effective means of propulsion. Most of the fishes meet these requirements very perfectly. The pointed head joins the body smoothly without intervening neck and there is a gradual taper from the mid-part of the body to the tail. A sculling motion of the tail region which bears a vertically expanded fin pushes the fish swiftly through the water. The aquatic reptiles likewise tend to modify the form of the body to reduce resistance and to develop the tail and limbs for swimming. Modification of the limbs for swimming, as shown by each type of the aquatic reptiles, consists in shortening and strengthening the upper limb bones, so that the propelling thrust of the paddle is brought near the body, and in shortening and spreading the bones of the lower limb. In some cases there is addition of phalanges

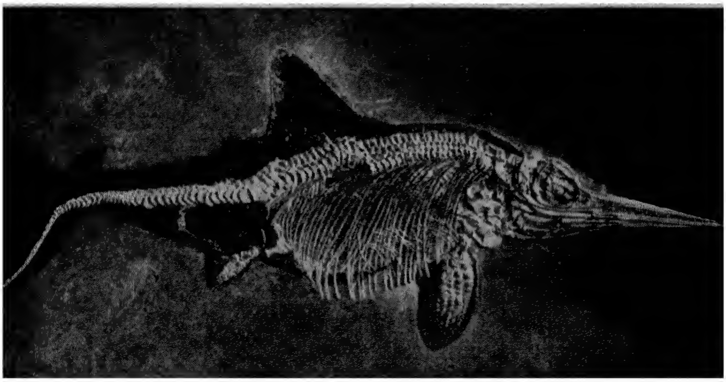

FIG. 280.—A fossil ichthyosaur showing not only the skeletal structure but by a carbonaceous residue the outlines of the body, paddles, and fins. Jurassic slates, Holzmaden, Württemburg, Germany. (*American Museum of Natural History.*)

which increases the length of the flexible part of the flipper. This is a good swimming organ but of no use on land. The four main types of aquatic reptiles are ichthyosaurs, mosasaurs, plesiosaurs, and turtles.

Ichthyosaurs, which lived from Triassic to Late Cretaceous times, attained a very remarkable external similarity to the fishes. The head was long and pointed, the jaws armed with sharp teeth adapted for catching prey but not chewing it; the head joined the body without a distinct neck; the rear part of the body tapered gracefully to a strong large tail fin, the spinal column bending sharply downward at the front of this fin; the limbs were shortened, flattened to a paddle shape; and there was even a dorsal fin that served as a keel in swimming. Further marks of aquatic adaptation are inferred in the circlet of bony plates in the eye which possibly lends protection against water pressures. The significance of these bones is somewhat doubtful, however, since similar ones occur in the eye of owls. The viviparous birth of the young is indicated by occurrence

of fossilized immature ichthyosaurs within the body of the mother. The later ichthyosaurs certainly could not have walked on land and the last need for going ashore was removed when the eggs, instead of being laid in the beach sand, developed within the mother. The gradual perfection of the highly developed ichythyosaur adaptations is seen in comparing some of the early with later species. At first, the limbs, modified as paddles, were the chief means of locomotion, the hind limbs as large as the fore limbs, the tail small, and the vertebral column nearly straight. Later the tail became the chief propelling organ, being much increased in size; the spinal column was bent abruptly downward at the union of tail and body; and the limbs, especially the hind limbs, were reduced in size. Ichthyosaurs probably fed on fishes and at least on some

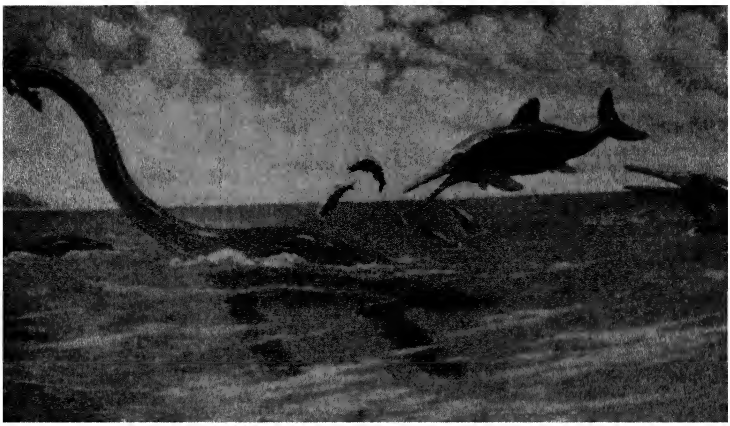

FIG. 281.—Plesiosaur and ichthyosaurs. (*C. R. Knight, Field Museum of Natural History.*)

invertebrates, for one specimen has been found with more than two hundred belemnite cephalopods inside the skeleton.

Mosasaurs are marine lizards that lived in the Cretaceous seas. The head was long and pointed, the body slender, the tail flattened, and the limbs paddle-shaped. The largest known specimens attained a length of about 40 feet. The University of Kansas has recently secured a giant specimen that will probably measure 50 feet long. A peculiar feature of the lower jaws was a double-jointed arrangement that enabled these animals to swallow prey larger than the normal gape of the mouth. Sharp recurved teeth not only lined the jaws but occurred on the roof of the mouth. Numerous well-preserved skeletons of these creatures have been found in the chalk of western Kansas.

Plesiosaurs are another distinct group of Mesozoic aquatic reptiles that appeared in Triassic times with imperfectly adapted form, culminated in the Jurassic, and persisted into the Late Cretaceous. Their chief characteristics were a small head and long neck (up to 76 vertebrae),

a short, broad, turtle-shaped body, and large powerful flippers which furnished locomotion. Plesiosaurs with a long head and rather short neck are known (*Trinacromerum*), but these are an exception to the rule. In general, the larger plesiosaurs had a length of about 20 feet, but *Elasmosaurus* from the Kansas Cretaceous had a neck 22 feet long and a total length of more than 40 feet. The form of these animals certainly seems inferior to that of the ichthyosaurs and mosasaurs as an adaptation to marine life, but the limbs are perfectly modified into oars. Generally speaking, the tail is a better swimming organ than paddles and the plesiosaurs were probably much slower and more cumbersome swimmers than ichthyosaurs or the majority of fishes. Rounded and smooth-surfaced "gizzard stones" have been found with plesiosaur skeletons.

Turtles are at home in the sea as well as on land. The body is rounded in outline and flattened above and below. It is encased in a bony and horny sheath, but in aquatic forms the bone tends to be reduced. Flippers furnish the means of swimming. A giant marine turtle (*Archelon*) from the Cretaceous had a length of 11 feet and a width across the front flippers of 12 feet.

Flying Reptiles

Some of the Mesozoic reptiles learned to fly and became eventually highly modified for life in the air. One group, called pterosaurs, developed a batlike form; another gave rise to the birds. How an animal gradually acquires a new mode of life and the accompanying necessary changes of body as radical as that in taking from the earth to the air is a problem that is not solved. Probably the first step is a development from jumping in which the upraised limbs give a slight support in the air and this leads to gliding. The flying squirrel really takes long jumps, gliding in the air on outgrown skin between body and limbs. From gliding to flying is a step that depends on further development of a supporting mechanism and on learning how to use it for sustained flight. If these are the lines of evolution, it yet remains to explain why and how the required structures of the body are produced to accompany the changed habits.

In any case, there is evidence among pterosaurs of the very perfect acquisition of the ability to fly. This is seen in the extreme elongation of the bones of the arm and one of the fingers to support a wing membrane, and also in the general lightening of the bones of the skeleton. The limb bones are hollow and air-filled as in birds. The wing of the pterosaurs differed from that of the bats in using only a single digit, the fourth finger, instead of four fingers. The power of sustained flight is also indicated by the occurrence of skeletons associated with marine animals, far from any existing land of the time when they lived. In size the flying reptiles ranged from that of a sparrow to the greatest of

nature's denizens of the air, past or present, for the late Cretaceous *Pteranodon* found in the chalk beds of western Kansas attained a wing spread of more than 26 feet. Yet the bones of even this huge pterosaur, made heavy by fossilization, weigh hardly 5 pounds. Its head bore a very long, sharp-pointed beak and also a nearly equally long bony crest, giving a most peculiar pickax-like appearance which was unlike other flying reptiles (Fig. 271*A*). Some pterosaurs had long tails, while others appear to have been tailless. Pterosaurs first appeared, as far as represented by known fossils, in the Late Triassic, and they persisted until the Late Cretaceous.

FIG. 282.—Skeleton of a flying reptile (pterosaur) as discovered on bedding plane of Jurassic beds. (*American Museum of Natural History.*)

Birds

The oldest known fossil birds are pigeon-sized creatures known as *Archaeopteryx* and *Archaeornis*,[1] practically complete skeletons of which are found in the Upper Jurassic limestone of Solnhofen, Germany.

The one distinguishing feature of birds is the possession of a body covering of feathers. Feathers are really marvelously complex, highly modified scales, which not inappropriately have been called "nature's masterpiece." *Archaeopteryx* and *Archaeornis* are birds because they had feathers. Otherwise these animals would certainly have been classed as reptiles. There is no birdlike beak; on the other hand, the jaws bear rows of sharp teeth like a lizard. The bones of the wing are not birdlike, with two of the three fingers fused together; instead, there are four fingers,

[1] Recent studies of the two Solnhofen fossil birds, both formerly classed as *Archaeopteryx*, have indicated the presence of differences deemed sufficiently important to warrant recognition of two distinct genera. The first discovered specimen retains the name *Archaeopteryx*, and the other one is named *Archaeornis*.

all free, bearing claws and with the same number of joints as the lizard. The tail is not birdlike, the feathers spreading in fan shape from a short projection of fused vertebrae; rather, it has a long axis composed of separate vertebrae as in the tail of a lizard, but a feather diverges obliquely on the right and left side of each vertebra. *Archaeopteryx* is a reptile except that it had primitive wings and tail and a partial body covering of feathers. This combination of characters representative of birds and reptiles is undoubtedly significant as to the ancestry of the birds. In

FIG. 283.—The oldest known bird, *Archaeopteryx*, from the Jurassic of Germany.

addition, there is indication of relationship between birds and certain of the dinosaurs and the pterosaurs. We may conclude that the birds and these others are all descendants of a single reptilian stock and that the birds began to develop avian characteristics at least as early as in the first part of the Jurassic period, or more probably in Triassic times.

There are two other interesting Mesozoic birds, both from Upper Cretaceous rocks. *Hesperornis*, known by complete skeletons and by impressions of its feathers in the fine-textured chalk, was a large swimming and diving bird. Its stretched-out length from tip of head to toes was as much as 6 feet. The main mark of a primitive stage in bird evolution is the possession of a full complement of sharp, slightly recurved reptilian teeth. Otherwise this creature had become as remarkably specialized for its mode of life as the modern penguin. *Hesperornis* had

entirely lost the power of flight; indeed, the wings are so rudimentary that they could not even be used as paddles as the penguin does in swimming. The feet were undoubtedly webbed and, with the long strong legs, were powerful in swimming. The joints at the pelvis, however, show that the legs could not be moved forward and backward as is the habit in modern swimming and diving birds, but they were moved sideward and outward. Such a spraddling motion is so ill adapted to walking on land that we may well question whether *Hesperornis* could get about except in the environment to which it had become fitted. Another type of bird whose remains occur very rarely in the beds containing the fossil just described is called *Ichthyornis*. This was a much smaller bird with very well-developed, strong wings. In general appearance there is closest resemblance to the modern sea gulls and we may accordingly picture this Mesozoic seabird as winging tirelessly above the widespread waters or dropping lightly to ride the waves like a petrel. But *Ichthyornis* also had teeth.

FIG. 284.—Head of *Archaeopteryx*. (*Restoration by G. Heilmann.*)

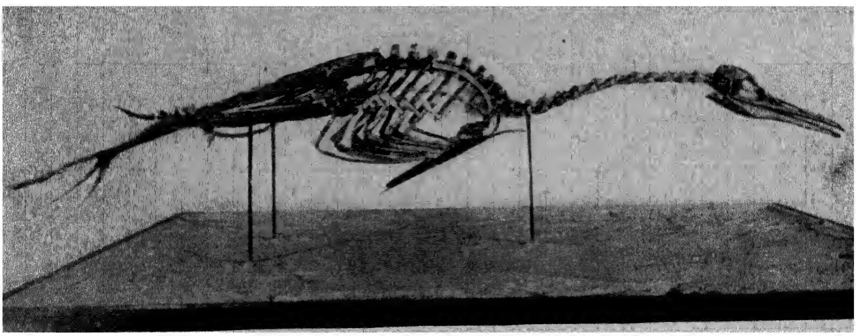

FIG. 285.—Skeleton of the toothed diving bird *Hesperornis*, from the Cretaceous chalk of western Kansas. The length of the specimen is nearly 6 feet. (*American Museum of Natural History.*)

There is a very wide gap between *Archaeopteryx* of Jurassic age and these Cretaceous birds. In spite of the fact that all have teeth, like their reptilian ancestors, there is really a greater difference in these early and late Mesozoic birds than between the latter and modern birds. It is clear not only from the general scarcity of fossil birds but much more from the specialized character of the Cretaceous birds that happen to have been discovered that the fossil record of the birds is very incomplete.

Mammals

Completion of our hasty scanning of the Mesozoic chapter of life requires consideration of the mammals, the stock to which man and the higher animals of the present belong. Remains doubtfully classed as mammalian are found in the Triassic, while more definitely recognizable primitive mammals occur in the Jurassic and Cretaceous rocks. They consist of teeth, lower jaws, and fragmentary parts of the skeleton, all of which show that these animals were diminutive, rather insignificant creatures. Two groups may be distinguished: (1) herbivorous forms with several tubercles on the teeth (multituberculates), and (2) probably insectivorous mammals, smaller than the first group and having sharp-cusped teeth.

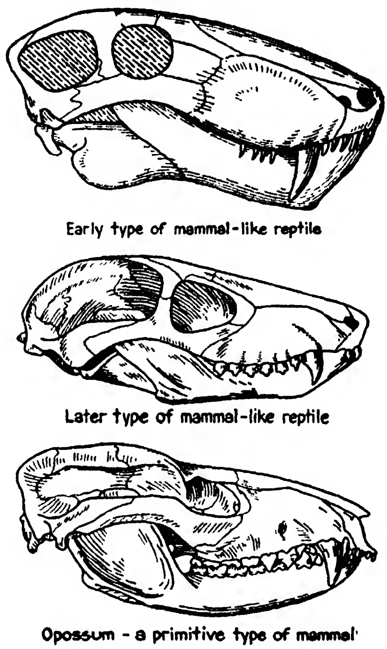

FIG. 286.—Comparison of the skulls of two types of mammal-like reptiles and of a primitive type of mammal. (*After Gregory, from K. F. Mather, Sons of the Earth, W. W. Norton & Company, Inc.*)

The multituberculates appeared in the Late Triassic and persisted to Eocene time. They are the most abundant and apparently, therefore, the most successful type of Mesozoic mammals. There is no evidence to show that they are ancestral to later kinds of mammals and it is very possible that their origin among mammal-like reptiles is different from that of the other Mesozoic mammals. Probably they were egg layers, but of this there is no proof.

The sharp-cusp-toothed mammals of probable insectivorous habits were small shrew-like creatures that appear to include the ancestors of the mammals of Cenozoic time. Most important are the trituberculates which are known from the Late Jurassic rocks of England and Wyoming and from the Late Cretaceous beds. Several primitive, tiny opossums occur in Cretaceous deposits of North America.

What little is known of the brains of Mesozoic mammals indicates that intelligence was low as compared with later mammals, but it was higher than that of any of the reptiles. It is certain that the mammals did not offer serious competition to the reptilian rulers of the Mesozoic world. Nevertheless, the mammalian line persisted, became gradually stronger, and, coincident with the decline of the dinosaurs, began to expand sharply and to branch out in many directions. The rise of the mammals to rulership of the lands is the main theme of the next following chapter in the history of life.

Amphibians

The beginning and rise of amphibians, the lowest type of land vertebrate, has been described in the chapter on Late Paleozoic life. The

Permian types almost wholly disappeared by the close of that period and a number of related new ones make appearance in the Triassic. Thereafter the amphibians sink to a place of little importance. The early Mesozoic amphibians belong chiefly to the broad and heavy-skulled labyrinthodonts, some of which were more than 14 feet long. Their bodies were bulky, the tails short and stumpy, and the legs so short that it seems they could hardly have carried the body without dragging it on the ground. It is probable that the weight of the body was buoyed up in the water most of the time. These large amphibians did not persist beyond the Triassic. The first of the batrachians (frogs and toads) appeared in the Jurassic period, and the first urodeles ("salamanders") in the Early Cretaceous.

Fishes

Practically all groups of known fishes are represented by fossils found in Mesozoic rocks. The appearance of the majority is distinctly

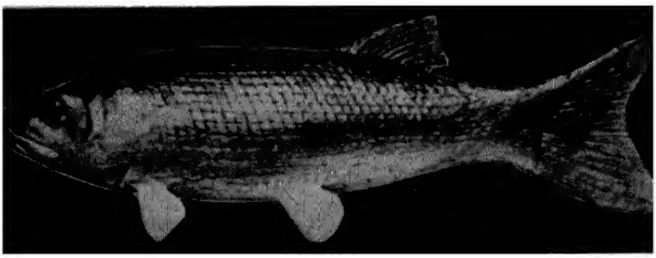

FIG. 287.—*Semionotus*, a common fresh-water type of Triassic fish, about 12 inches in length. (*Ward's Nat. Sci. Estab.*)

more like that of modern types and the structural character of the skeleton, scales, and fins trends strongly toward those dominant today. Especially important is the introduction of the teleosts, or true bony fishes, which include approximately 90 per cent of living kinds of fishes.

Description of the evolution of the Mesozoic fishes in detail is not appropriate here, partly because of the technical terminology and the multiplicity of features that are involved and partly because the fishes are greatly overshadowed by interest in the higher vertebrates of the lands and seas, especially the reptiles. Moreover, fish remains are generally less important as index fossils than either invertebrates or reptiles.

The Triassic strata of the Atlantic Coast region have yielded an interesting assortment of well-preserved fish fossils which show the regularly arranged rhombic scales of the body, the fins, and the plates of the head, but reveal little of the partially ossified skeleton. The fishes lie on their side and are flattened to paper thinness on bedding planes of the rock. Jurassic fishes are very rare in North America but are not uncommon in Europe.

The Cretaceous marine deposits of the United States contain fairly abundant fish remains. Shark teeth of various sorts, some sharply pointed like those of modern sharks and others broadly flattened for crunching and grinding, are collected from

many outcrops of shale and chalk. Fish scales are common fossils in many Cretaceous beds and are especially characteristic of some. A few types are as much as an inch in diameter. The long bony fin spines, vertebrae, and whole fossils showing scales and fins or preserving the complete bony skeleton are found. Some of these fishes, as *Portheus*, attained a length of 15 feet and, as indicated by the numerous large pointed teeth, were fiercely predaceous in habit.

Some of the main features in the Mesozoic history of the fishes appear to be (1) the dominance in fresh waters of the "ray-finned" bony fish (actinopterygians), which are types leading to the teleosts, (2) the invasion of the sea by this group which in Paleozoic time appears to have been restricted to fresh water, and (3) associated with this marine adaptation of the bony fishes and possibly also the appearance of abundant new mollusks, a revival of sharks, skates, and rays, which had nearly disappeared at the close of the Paleozoic era.

FIG. 288.—Skeleton of the large marine fish *Portheus*, of Late Cretaceous age. Some specimens of this fish are 15 feet long. (*University of Kansas*.)

Cephalopods

The most interesting of the marine invertebrates of Mesozoic time are the cephalopods. They are also one of the most abundant, widespread, and stratigraphically important classes. The four-gilled, external-shelled types are dominant and include both nautiloids with simple sutures and ammonoids with very complex sutures. The two-gilled cephalopods (belemnoids, sepioids) with internal shell also occur and in some strata are abundant. They will be described in a later part of this chapter.

Ammonoids.—The beginning of the specialization of external-shelled cephalopods that culminated in the exceedingly complex Mesozoic ammonoids dates back to the Silurian period. The development is chiefly manifested in (1) increasing complication of the sutures and (2) external ornamentation, but also (3) by the form of the shell, (4) modifications of the aperture, and (5) increase in size.

The sutures (junction of the shell partitions with the inner wall of the shell) are only moderately curved or angulated in the simplest ammonoids. This type was characteristic of the later Paleozoic rocks but some of the ammonoids of the Triassic are little, if any, more advanced.

An increased number of bends and angles in the suture line, accompanied by a progressive complication in pattern, marks the development of most of the Mesozoic ammonoids. In many cases the suture pattern is so intricate that it is indeed difficult to trace. The diversity is amazing, but each type of suture is constant according to genus and species. Because even slight changes in the sutures are readily determinable and with other characters permit definite recognition of specific differences, these shells are well fitted to serve as markers of stratigraphic zones and

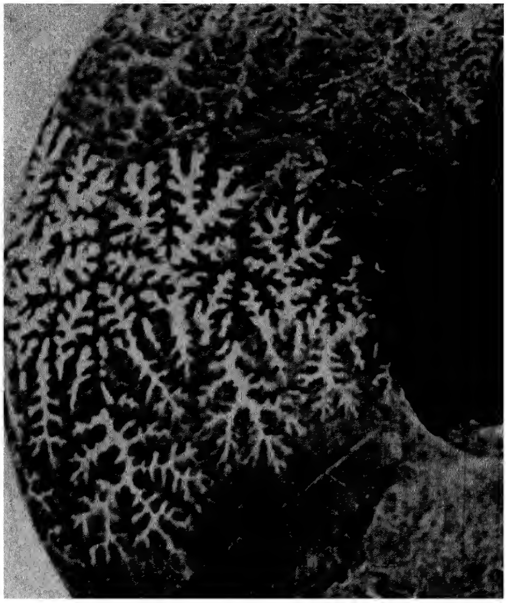

FIG. 289.—Portion of the shell of a very complexly sutured Cretaceous ammonite, *Pachydiscus*, from Lower California. The space between two adjacent sutures has been painted white (about one-fourth natural size). (*University of Kansas.*)

of geologic time. Because they lived in enormous numbers, were distributed all over the world, and underwent comparatively rapid change, they are excellent index fossils.

External ornamentation of the ammonoid shells consists of lines, ridges, nodes, or spines, and the variety of form and arrangement of these is very great. Some shells are smooth but the vast majority carry some sort of surface decoration. Around the outer margin or venter of many of the coiled shells is a ridge or keel; in others there is a groovelike depression; and in still others this part of the shell is not differentiated by its markings.

The form of ammonoid shells shows much variation. All but a few types are coiled in a plane but of these some are evolute, all of the whorls being completely visible from the sides; others are highly involute, the

outer whorl concealing all of the inner ones. The cross-section of the shell ranges from very narrow and laterally compressed to very broad and vertically flattened. In several families there are genera with the elevated spiral shell which is typical of most gastropods but is abnormal among the cephalopods. A few specialized, degenerate types have shells with very erratic twists and bends. Others show reversion toward an ancestral primitive state in the tendency to uncoil and even straighten out. These peculiar aberrant forms appear chiefly toward the close of the career of the various branches of the ammonoids. They are a mark of approaching extinction.

The aperture of most ammonoids, where known, is unconstricted and the edges of the shell mouth are smooth or gently curved. In some, however, the lateral margins are extended very prominently forward, or the ventral portion of the shell projects considerably like a beak. A few of the ammonoids, like certain Ordovician and Silurian nautiloids, exhibit markedly narrowed, abnormal apertures, which must be considered as an overspecialized character presaging disappearance of these evolutional branches. The aperture in some genera was closed by a lid (*aptychus*).

The normal size of the average Mesozoic ammonoid is measured by a few inches for the diameter of the coiled shell. There are some dwarflike but apparently adult shells that are less than ¼ inch across. On the other hand, many genera are characterized by robust size, with shells more than a foot in diameter and a few attained gigantic proportions, measuring 5 feet or more across. If the shell of one of these mammoth forms could be uncoiled, it would measure not less than 20 feet in length.

Study of the distribution of ammonite species in the Mesozoic rocks shows not only that a large proportion are restricted to a narrow vertical range, making them valuable as index fossils, but that in a broad way the genera and families of the Triassic are almost wholly distinct from those of the Jurassic, and in turn those of the Jurassic from those of the Cretaceous. It is as though all but one branch of a healthy tree were suddenly cut off and all of the branchlets of the remaining branch were also pruned away. Vigorous growth brings remarkable development of the remnant branch, however, and a multitude of new branches, large and small, springs out from it. Again the tree is cut back, and, though a few hardy portions struggle on with fitful promise, in the end they all sicken and die. Of more than 2,600 known Triassic ammonoid species, none continued into the Jurassic and the host of later species and genera, quite as numerous as those of the Triassic, were derived from a single surviving small group.

The abundance, variety, and complexity of the evolutional modifications of the ammonoids during the heyday of their development in Mesozoic time, followed by the rapid decline and utter extinction of so

prolific a stock, constitute a truly remarkable chapter in the record of life on the earth. It is paralleled, however, by the history of various

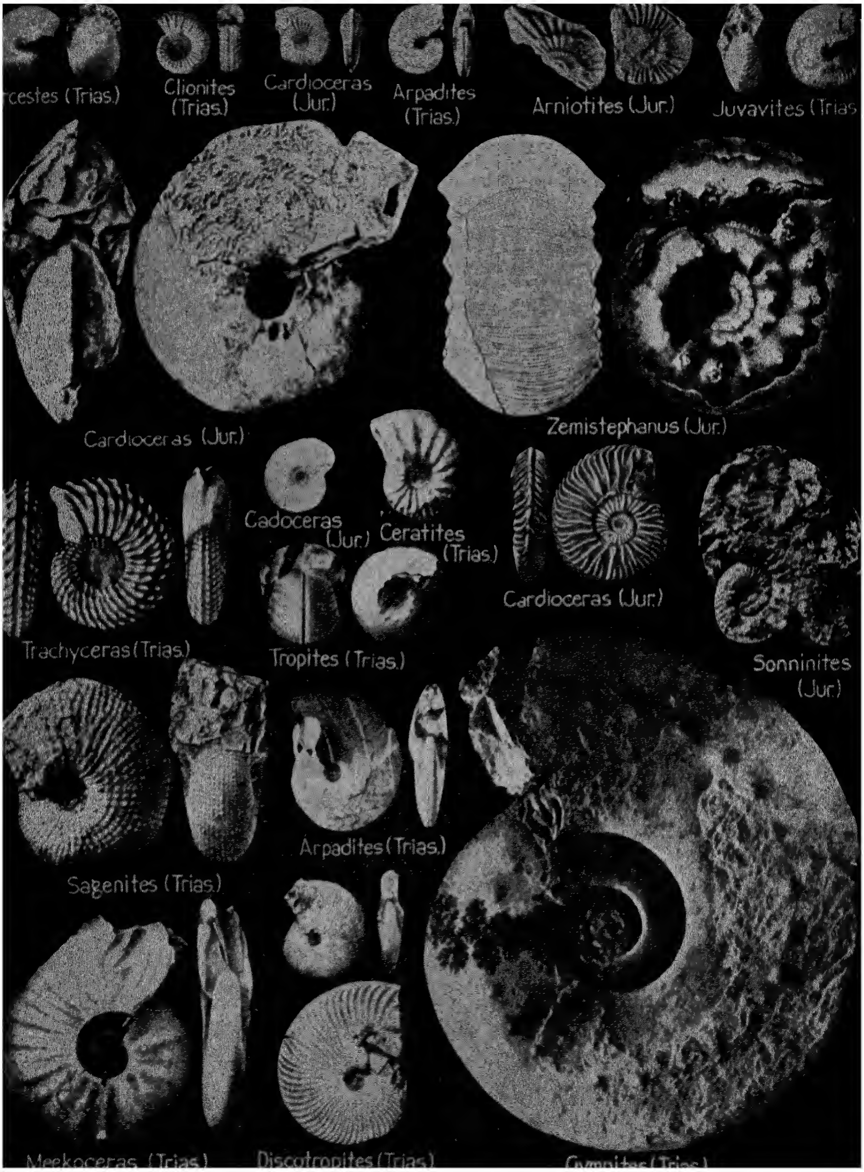

Fig. 290.—Representative types of Triassic and Jurassic cephalopods (about one-third natural size).

other classes of animals and plants that more or less slowly advanced to a certain point, then expanded almost explosively to a wonderful peak,

only to decline to a pitiful remnant of their former greatness, or to vanish entirely. This seems to be one of the lessons of life—adolescence, adult virility, senility, death. Climax is followed by swift denouement and

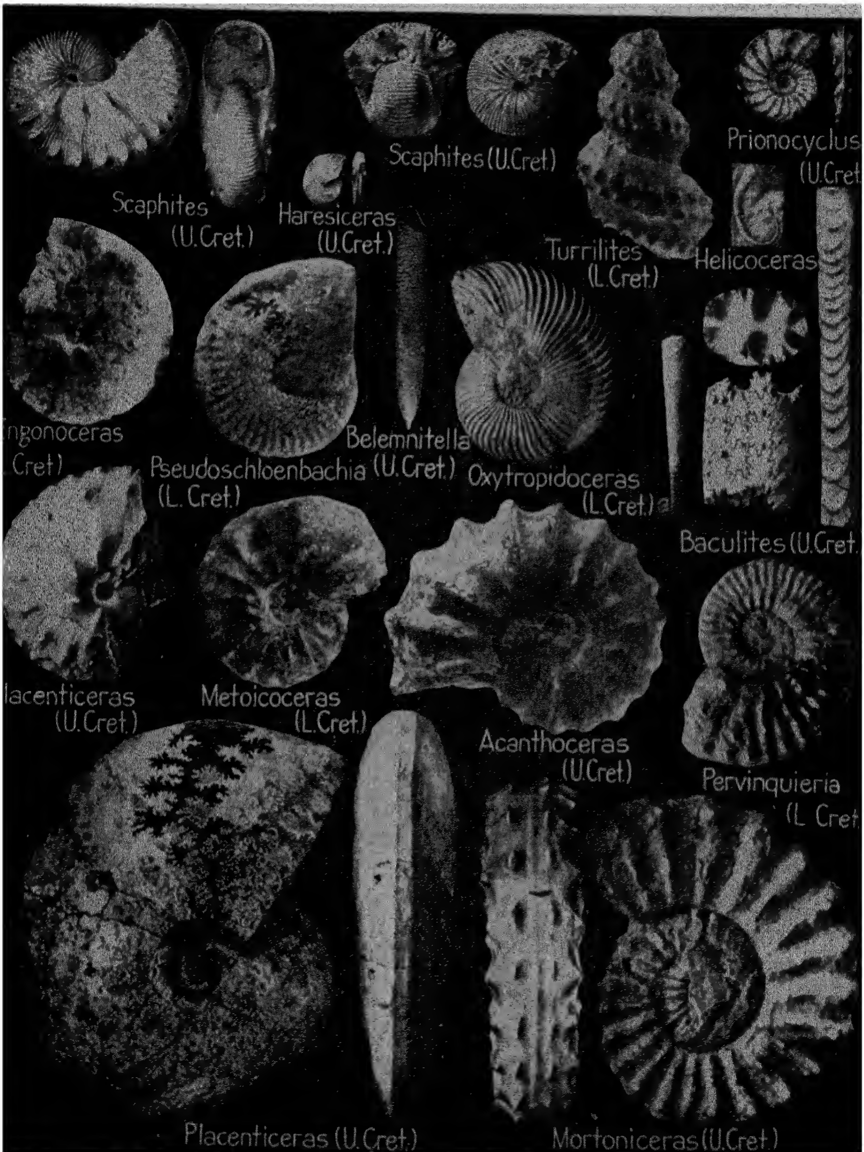

FIG. 291.—Representative types of Cretaceous cephalopods (about one-third natural size).

the play is ended. The fall of the curtain is preceded, on the one hand, by appearance of overspecialization and exaggeration that produce freaks and caricatures; on the other, by degeneracy that reverts to primitive characters.

Nautiloids.—Although almost completely overshadowed by the host of ammonoids, the simpler external-shelled cephalopods, the nautiloids, were not rare in Mesozoic seas. Most of them were tightly coiled and deeply involute like the modern nautilus, and some attained a diameter of more than 12 inches. There is a distinct tendency in some toward complication of the sutures, such as marked the ammonoid branch, but this did not proceed farther than development of a few rounded, though well-defined, inflections (lobes and saddles).

Belemnoids.—The two-gilled (dibranchiate) cephalopods, to which belong the modern squids, cuttlefishes, and octopuses, are interesting creatures that boast a respectably ancient lineage, but the importance of their geological record is much less than that of their cousins, the ammonoids and nautiloids. And among the dibranchiates we are almost entirely concerned with those called belemnoids (see Fig. 122).

The body of the belemnoid is elongated, cylindrical, and pointed at the posterior end. The head bears a circlet of 10 powerful muscular tentacles,[1] the inner sides of which are armed with rows of little hooks. The abdomen contains besides the viscera a rather large sac called the ink bag, for it is filled by an extremely opaque brownish-black fluid that can be ejected at will by the animal so as to form a dense cloud in the water and conceal retreat. This ink bag is sometimes represented in fossils by a dark-colored carbonaceous residue.

The shell of the belemnoids is internal and consists of three parts: (1) a chambered cone that somewhat resembles a simple, straight-shelled nautiloid, (2) a delicate shoehorn-like projection extending forward from the mouth of the cone on the dorsal side, and (3) a solid cigar-shaped piece that fits around the pointed end of the cone and extends some distance beyond it. It is this last, called the guard or sheath, that is most commonly found as a fossil. It shows a fine prismatic, radiating structure around the long axis.

Most common and widespread of the belemnoids are specimens of the genus *Belemnites* and its close relatives, of which more than 350 species are known from Jurassic and Cretaceous rocks. In some strata, shells of this type occur by the millions, and they are known all over the world. The name belemnite was first used nearly four hundred years ago by Agricola; it means thunderbolt and refers to the fancied resemblance of these fossils to the weapons of the gods.

Pelecypods

These bivalved, bottom-dwelling mollusks have been noticed in our survey of the life characteristics of the Paleozoic periods. They were then common locally, varied in form but altogether a conservative, rela-

[1] Evidence of eight arms only is found in fossils. The two others, as in certain modern dibranchiates, were probably longer than the rest and without hooks.

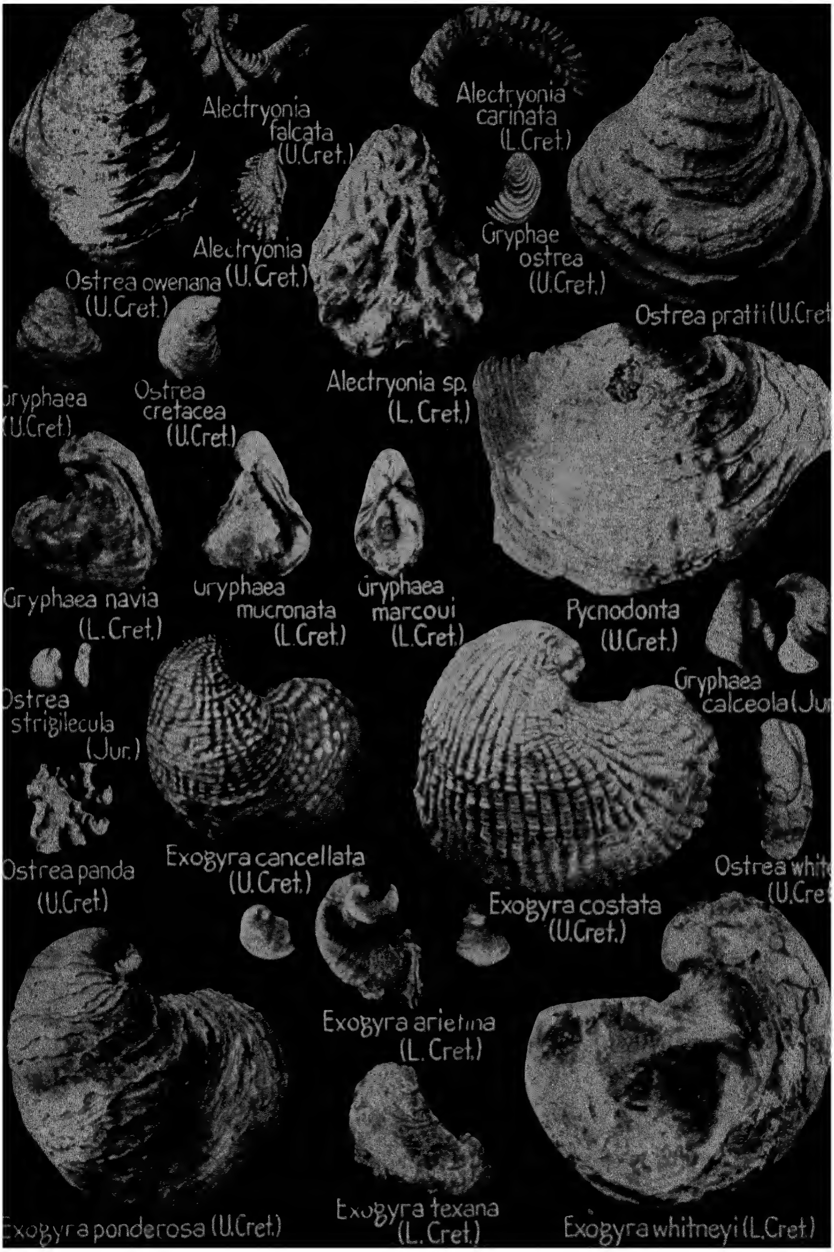

Fig. 292.—Fossil oysters and related pelecypods of Mesozoic age (two-fifths natural size). Most of these shells are good index fossils.

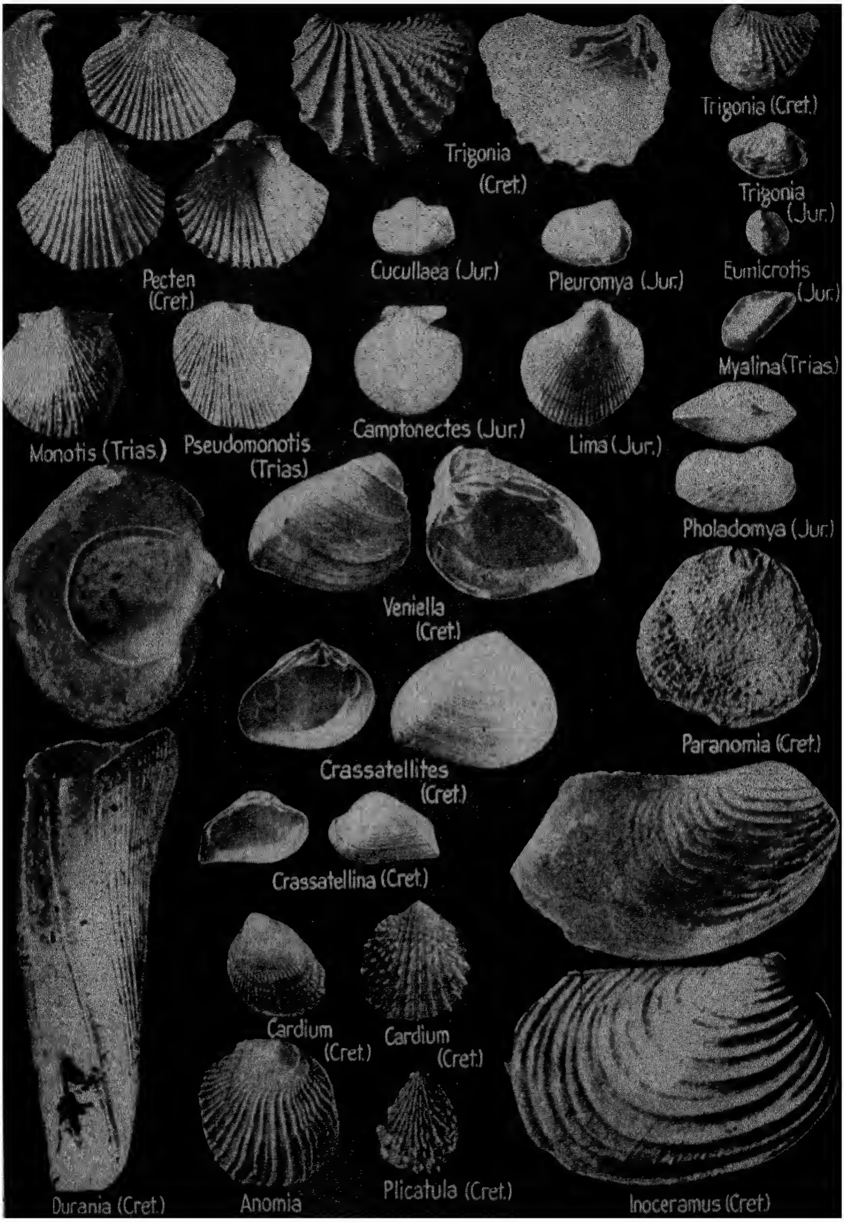

Fig. 293.—Representative types of Mesozoic pelecypods, excepting the oyster group (about one-third natural size).

tively simple class of animals that was distinctly secondary in importance as an element in the faunas. A gradual but marked change is seen among pelecypods of Mesozoic times. Many of the ancient types lived on into this era but the majority of species acquired a higher type of structure as indicated in the more complexly specialized hinge teeth and other features, and the actual and relative numbers gave them a much more prominent place in the life assemblage. Several distinct groups became important. Some were beautifully ornamented; some developed a more peculiar and strangely specialized form than any other known pelecypods; and some attained a huge size that probably exceeds all others of this class. Only a few of the chief types, however, can be described here.

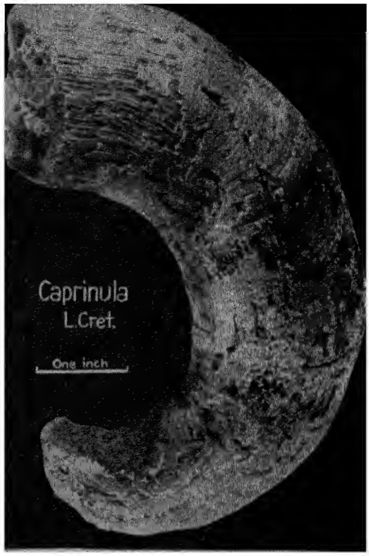

FIG. 294.—A highly specialized sessile pelecypod of coral-like form, from west Texas. (*W. S. Adkins, University of Texas.*)

One of the most important groups was that of the oyster (*Ostrea*) and its allies. The first oysters had appeared in Carboniferous time but during the Mesozoic they expanded remarkably and were much more important than today. Distinguishing features of the oyster family are the distorted form and unequal size of the two valves which results from the cementation of the shell to foreign objects during part or all of the life of the animal, the presence of only one instead of two muscles to hold the valves together, and the absence of distinct hinge teeth. The larger, deeper valve is beneath and the smaller, generally nearly flat opposite valve is above, fitting over the other like a lid. Some of the Mesozoic oysters were not unlike modern kinds, but there is a tendency toward radiating ribs or plications. Two members of the oyster family that were especially abundant and important horizon markers in the Jurassic and Cretaceous rocks are *Gryphaea* and *Exogyra*. Some specimens of these had a shell in the lower valve nearly 2 inches thick. The little ram's horn *Exogyra* (*E. arietina*), which marks a zone near the top of the Lower Cretaceous, has a spirally twisted larger valve. In places the oyster shells of each of these types are so numerous that rock layers several feet thick are mainly composed of them, and when the strata disintegrate the ground may be literally blanketed with fossil shells. One of the most common and widely distributed pelecypods in some of the Cretaceous formations is called *Inoceramus*. The shell is rounded

in outline and marked by prominent concentric grooves and ridges. A few species attained gigantic size, measuring 3 or 4 feet across. Like *Gryphaea* and *Exogyra* they include many good index fossils.

The subtriangular shells of *Trigonia*, distinguished commonly by ornamentation of nodes or ribs that differ in the anterior and posterior portions of the shell, are characteristic of Mesozoic formations. They are relatively most prominent in rocks of the Jurassic system.

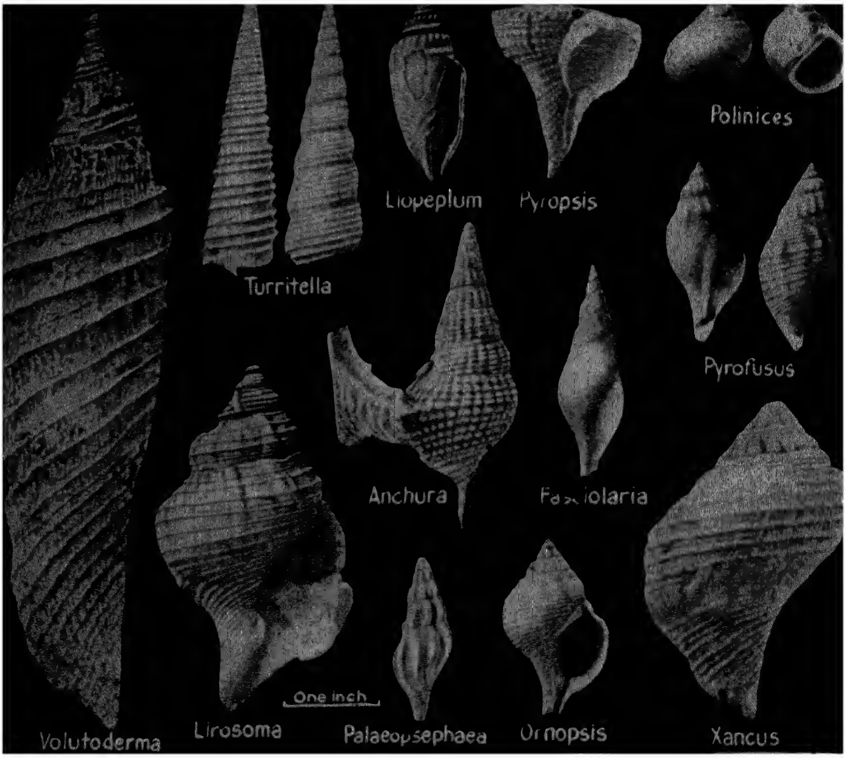

Fig. 295.—Some types of Cretaceous gastropods.

In the middle and especially the late part of Mesozoic time there developed some of the strangest and most peculiarly specialized of known pelecypods. These are the Chamacea, which have an exceptionally strong spiral growth of the very unequal valves (Fig. 294), and the rudistids, which have the form of a horn coral covered at the top by a nearly flat lid (*Durania*, Fig. 293). The shell walls of the latter may be excessively thick and the height of the coral-like lower valve more than 2 feet. The abnormal features of these pelecypods are evidently the result of a sedentary, fixed mode of growth on the sea bottom where they generally lived in closely crowded colonies, the remains of which may form thick

beds of limestone. The chamacean and rudistid pelecypods abound in the warmer-water deposits of Cretaceous time and they mark an evolutional offshoot that, except for one or two of the more conservative types, did not survive into the Cenozoic.

Fresh-water mussels (*Unio* and others) are common in some of the Mesozoic continental formations.

Gastropods

Gastropods are a common but not a dominant element in the invertebrate life of the Mesozoic. Many of the species belong to well-established families that date back to Early Palezoic times, but a very large number of new families representing the more advanced biological orders are introduced during the era. The latter are characterized externally by various ornamental features, but especially by the presence in many of a tubelike elongation of the shell in front of the aperture, that is, at the end of the shell opposite to the spire, for accommodation of a siphon. Species of gastropods belonging to the pulmonate, or air-breathing group, are known in some Mesozoic continental deposits. Many of the Mesozoic gastropods are useful index fossils.

Echinoderms

Echinoids.—The sea urchins or echinoids, which are common on parts of the shallow sea bottom today, were represented by archaic types in the Paleozoic era. During Mesozoic time they began the climb toward their present position of prominence. Fossil echinoid remains are very abundant and widespread, especially in the Jurassic and Cretaceous rocks. Since the main characters of these animals have not been discussed previously, they may be described here.

The echinoids are distinguished from other echinoderms by the general form and plan of their shell, but especially by the covering of the shell by innumerable movable spines. In one large group of echinoids the shell is a slightly flattened globe with a moderately large opening for the mouth, centrally located on the under side, and a small anal aperture near the center of the dorsal side. The shell is composed of 20 columns of plates arranged in double rows, five of the pairs of rows containing specialized perforated plates (*ambulacra*) through which the delicate "tube feet" or tentacles that are used in locomotion or for respiration are protruded. The spines vary greatly in size and there may be two or three orders of sizes on the same shell. They have a socket-like hollow at the base which articulates with a rounded tubercle on the plates of the shell and is movable by muscle fibers that are attached slightly above the base. The function of the spines is to support the test, to aid in locomotion, and to serve as a means of defense. Within the mouth of most echinoids is a masticatory apparatus known as Aristotle's lantern.

A second group of echinoids is distinguished by the more or less irregular outline of the shell which in a large number of species is heart-shaped, by the excentric position of the mouth and anus, and in part by

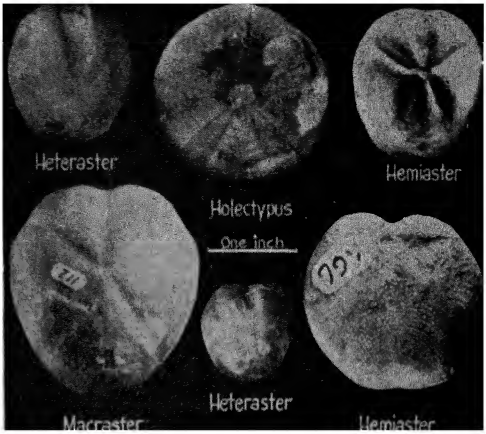

FIG. 296.—Representative types of Cretaceous echinoids. (*W. S. Adkins, University of Texas.*)

modification of the ambulacral areas into petal-shaped spaces on the dorsal side of the shell.

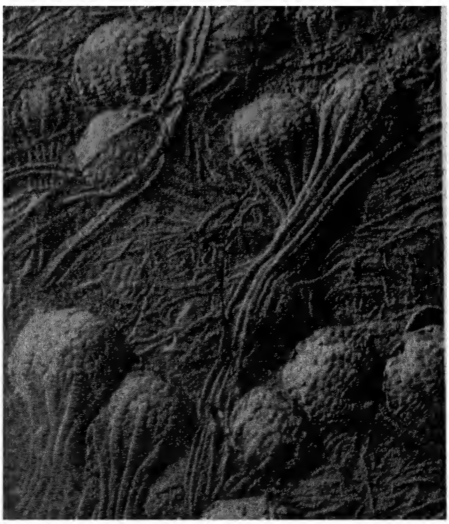

FIG. 297.—A small portion of a slab covered with specimens of the free-swimming Cretaceous crinoid *Uintacrinus*. From the chalk of western Kansas (one-fourth natural size).

The Mesozoic history of the echinoids records (1) the rapid increase in numbers and variety, and (2) the progressive specialization of each

group, (a) the regular echinoids toward increased spinose ornamentation, in some cases with very peculiar spine development, and modification of the ambulacra, and (b) the irregular echinoids toward increased eccentricity of position of mouth and anus and a marked bilateral instead of radial symmetry. Many echinoid species are important index fossils.

Crinoids.—The Mesozoic crinoids, like the corals, are more like those of the present than any of the hosts that lived in Paleozoic time. Excepting one genus that persisted in the Triassic, all of the Paleozoic kinds of crinoids had disappeared before the close of the Permian. A new order, the Articulata, which includes the Mesozoic and modern crinoids, appeared in the Triassic. Some of the Mesozoic crinoids were very widely distributed but only locally were they common.

The most interesting fossils of this class in the Jurassic rocks are specimens of *Pentacrinus*, which show in some cases 20 feet or more of the stem, bearing closely crowded branchlets (*cirri*) and the complete calyx with attached arms, which form a crown measuring as much as 3 feet in height and width. It has been estimated that the entire length of stem in some *Pentacrinus* individuals may have been more than 50 feet, exceeding greatly any other known crinoid. The separated stem segments, like small five-pointed stars, are not uncommon in American Jurassic marine strata, but well-preserved crowns that are exhibited in many of our museums come from Europe.

An equally striking but very different kind of crinoid is *Uintacrinus* of Cretaceous age. This was one of the free-swimming stemless crinoids known as comatulids. Its globular calyx is but a few inches in diameter but its arms may be as much as 4 feet long, considerably greater than in any other crinoid. *Uintacrinus* is known in England, Germany, France, Australia, and western America, especially in Kansas, from which the most remarkable specimens come. These are found on thin sheets of limestone, the surface of which is crowded as closely as possible with beautifully preserved individuals with arms attached. Another stemless crinoid that is characteristic of Cretaceous time is *Marsupites*.

Brachiopods

This class of shelled animals which had been so abundant and varied in the seas of Paleozoic times is almost pitifully reduced in the Mesozoic era, although locally there were very numerous individuals belonging to a few species. The most important persisting types were smooth-shelled and more or less simple in outline (Terebratulacea). They are characterized especially by the nature of the internal calcareous support for the brachia which is in the form of a loop. Angularly plicated shells with pointed beaks and without calcified brachial supports (Rhynchonellacea) are also common locally. The spire-bearing brachiopods (Spiriferacea) were represented by a few forms that lasted until Early Jurassic time, but the great host of these shells is restricted to the Paleozoic. Lastly there were the very simple, thin-shelled calcium phosphate types like *Lingula*, which has persisted practically unchanged from very early Paleozoic time down to the present day. Altogether the brachiopods of the Mesozoic are a declining race, but it is interesting to observe that the kinds that survived the changes of closing Paleozoic time are, in the main, the simple and conservative in structure, neither highly specialized nor degenerate, and some of these have been able to adapt themselves to the varying conditions of later geologic history.

Bryozoans

The abundant Paleozoic bryozoans belong chiefly to two orders which are restricted to that era. Those of the Mesozoic, and also of later time, belong almost wholly to

two other orders, Cyclostomata and Cheilostomata, the latter of which first appeared in the Jurassic. The cyclostomes have very simple cylindrical tubes and rounded apertures, but the form of the colonies is greatly varied. The cheilostomes, on the other hand, have a complex organization. In many of them is a mechanism (*compensation sac*) that serves to extend the animal from its little cell (*zooecium*) and in all cases the cell aperture may be closed by a movable lid (*operculum*), the shape and ornamentation of which is found to be of much value in classification. This bryozoan group expanded astonishingly during Cretaceous time and has been important ever since.

The French paleontologist d'Orbigny has described more than eight hundred species of Upper Cretaceous bryozoans.

Crustaceans

Trilobites did not survive the close of the Paleozoic era, but a great number and variety of other crustaceans, some of them surprisingly like modern species, occur as fossils in Mesozoic rocks.

Ostracodes are very numerous in many of the Mesozoic strata, but they belong almost wholly to types unknown in Paleozoic rocks. On the other hand, a majority of the Mesozoic ostracode genera have persisted to the present day. These fossils are a valuable aid in identifying formations and zones encountered in wells that penetrate the Cretaceous rocks of the Gulf Coast and some other regions.

Cirripeds, the barnacles, are fairly well-known in Cretaceous beds, though seldom common fossils. Some of them are much like living species.

Higher crustaceans of many sorts, including the lobsters, crayfish, crabs, and other kinds, make their appearance during the Mesozoic. Remarkably preserved specimens in which all of the appendages are complete occur in some deposits, especially the famous Solnhofen limestone, of Jurassic age, in Germany. An interesting group that is well represented in Jurassic and Cretaceous rocks is that of the decapods.

Insects

As now known from a series of wonderful fossil insect collections of Pennsylvanian and Permian age, many important insect orders had been established before the beginning of Mesozoic time. The best record of insects in the Mesozoic comes from Jurassic rocks in Europe, the Triassic having few and the Cretaceous almost no good fossils of this sort.

Besides cockroaches, dragon flies, and other "first families" among the insects, the Mesozoic rocks contain representatives of the true bugs (*Hemiptera*), both terrestrial and aquatic; the flies (*Diptera*), with some 30 Jurassic species; butterflies and moths; the ants, wasps, and bees; beetles; locusts and crickets; plant lice; caddis flies; scorpion flies; lacewing flies; and May-flies.

Protozoans

The important fact about fossil protozoans during Mesozoic time is their abundance and great variety in the Cretaceous rocks. The chalk and chalky limestone deposits of this age, which are practically world-wide in occurrence, contain multitudes of the minute shells of Foraminifera. The geologic formations penetrated by drilling in the oil-field region of Louisiana, Texas, and northeastern Mexico are successfully identified by study of the shells of Foraminifera washed from the well cuttings. In this connection may be noted the discovery at shallow depth in certain Gulf Coast oil wells of abundant Cretaceous species of Foraminifera mingled with Tertiary species, the age of the rocks being evidently Tertiary. The fact that the Cretaceous types are all slightly worn, while the others are fresh and unmutilated, supports the

conclusion that the older shells were weathered and transported from some Cretaceous outcrop and redeposited with shells of much younger species that were living at the time.

Little is known of protozoans during the Triassic period. They were fairly abundant in Jurassic time, the majority of species resembling Cretaceous forms. Several modern types originated but not very many kinds are known.

Sponges

Both siliceous and calcareous sponges are abundant in some of the Mesozoic rocks. The former occur in limestones but the latter only in sandy or muddy sediments deposited in shallow near-shore waters. This accords with conditions in living species, for the siliceous sponges inhabit moderately deep water, while the calcareous types

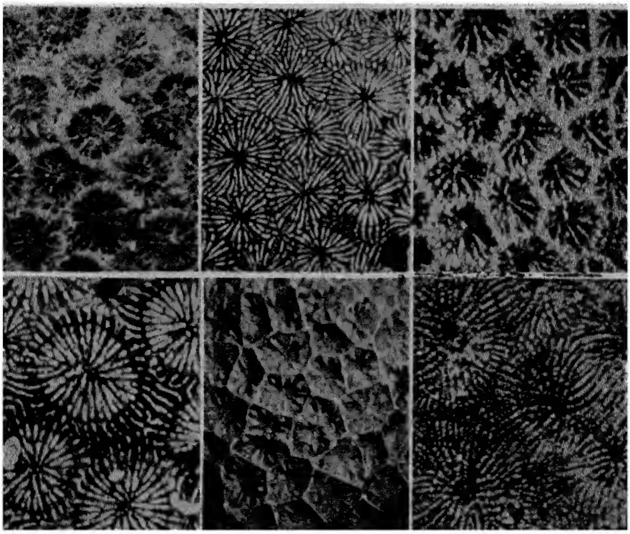

FIG. 298.—Some Cretaceous colonial corals from Texas (about × 2). (*After Wells.*)

predominate in shallow water. The chief development of siliceous sponges (especially the lithistid group) in Mesozoic time is seen in thick beds of sponges, highly varied in kinds, in Jurassic limestones of central Europe and again in the Upper Cretaceous of western, central, and southeastern Europe. The common occurrence of flint and chalcedony in many of the Mesozoic formations, especially in parts of the Cretaceous, indicates that siliceous sponges of the more primitive sorts were also abundant and important as rock builders, for the separated skeletal elements (spicules) of these largely supply the silica. Many kinds of calcareous sponges appear in the Triassic rocks of the Alps region, in parts of the European Jurassic, and in the Cretaceous. There are sponges in the American Cretaceous beds but they are not a prominent element in the faunas.

Coelenterates

Corals.—The corals of Mesozoic time are similar to those living in the warm shallow seas of the present day and both of these differ from the ancient Paleozoic corals in having a basic hexameral or sixfold symmetry. The sixfold structural

plan is very clearly seen in the size and arrangement of the septa in many genera which show six main septa and more or less numerous subordinate ones, but it is more obscure in others. Both single horn corals and compound, colonial types occur, but the latter greatly predominate. Most of the genera are rather long-lived, persisting through two or more of the Mesozoic periods, and some have lived from the Triassic to the present.

In North America, most of the Mesozoic rocks contain few corals, partly because marine deposits are restricted, except in the Cretaceous. In Europe, however, there are large numbers of reef-building hexacorals in some of the Triassic formations of the Alps region. Limestones up to 4,000 feet thick, mainly composed of reef corals, are found in this area (Schuchert). The Jurassic is especially rich in corals at very many places and they occur in high latitudes as well as in the equatorial belts, indicating widespread warm waters. The Lower Cretaceous beds locally contain many corals but only in Holland and Denmark are they common in the Upper Cretaceous. Maximum numbers and variety as well as widest geographic distribution belong to Jurassic times.

Hydrozoans.—Two types of hydrozoans are represented among Mesozoic fossils. One of these consists of colonial polyps that secrete dense calcareous layers at the base, forming a deposit very much like that of the Paleozoic stromatoporoids. Some of these lime-secreting hydrozoan colonies were especially abundant in the Mediterranean region in Jurassic time. The other hydrozoan type consists of *jellyfishes*, which though they contain no hard parts are known from remarkably perfect impressions in the very fine-grained lithographic limestone of Jurassic age at Solnhofen, Germany, and in some flinty concretions of Late Cretaceous age. The Solnhofen beds are famous for the variety and perfection of their fossils, which include in addition to common marine invertebrates, several kinds of insects, marine reptiles, and, most interesting of all, the two only known specimens of the earliest birds that have been discovered.

MESOZOIC PLANTS—THE AGE OF CYCADOPHYTES

In terms of plant life, the Mesozoic era may be called the "Age of Cycadophytes," because cycad-like plants, which are comparatively unimportant in modern floras, dominated the plant assemblage of the earth's Mediaeval time.

General Character of Mesozoic Floras.—Notwithstanding the fact that the plants of Mesozoic time are the direct descendants of Late Paleozoic species and that several of the latter types lived on essentially unchanged well into the Triassic period, the floras of Mesozoic age are distinctively new and different. The dominant plant group was that of the palmlike cycadophytes, to be described presently, but nearly equal in number of species were ferns and conifers. Most of these were short or only moderately tall, so that one of the main contrasts with the Carboniferous floras consists in the absence of gigantic lepidophytes and cordaites. The horsetail family had several generic representatives, among which some of the very early Mesozoic forms were colossal. The ferns were relatively small, quite unlike the Paleozoic vine- and treelike seed ferns. A common type of early Mesozoic fern, called *Cladophlebis*, had its beginning in the Early Permian. A general exception to the small average size of Mesozoic plants appears in some of the conifers which

grew to a height of more than 100 feet. In Late Mesozoic time the angiosperms, highest type of seed-bearing plants which are dominant today, were introduced and became the most important element in the vegetation of all lands.

The Cycadophytes (*Cycadophyta*)

This interesting plant group which is characteristic of the Mesozoic era is closely related to, but yet quite distinct from, the modern cycads, which are represented by many living species in the tropics and subtropical regions. Cycads have a woody trunk with a large central pith cavity and the outer part cloaked by a mat of hanging dead leaves or

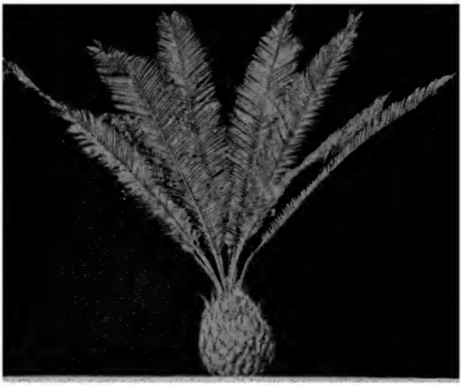

FIG. 299.—A type of living cycad (*Dion edule*) that resembles in form some of the common Mesozoic cycadophytes. (*After Wieland.*)

bearing closely spaced pitted scars that mark the place of former attachment of the leaves. The trunk is very short and bulbous in some species, about as wide as high, but in others it attains a height of more than 50 feet. At the top is a graceful crown of long, palmlike leaves which have a strong stem axis and very numerous narrow elongate leaflets on the two sides. In a few cases the leaflets are themselves divided into a double row of tiny secondary leaflets which gives the frond a decidedly fernlike appearance, and this is enhanced by the coiled-up tips of young leaf shoots just as in the ferns. There is a large cone at the crest of the cycad in most living species, containing the reproductive elements. The most common fossil cycadophytes had very interesting true flowers in which a circle of male spore-bearing stamens surrounded a pear-shaped female organ with numerous seed ovules. The male and female flowers are separate in some fossils, though both may have been borne by the same plant.

The cycadophytes had their beginning late in the Paleozoic era but they are not satisfactorily known until Late Triassic time when they appear to be well established. Some 40 different cycadophyte species have been recognized in the coal basin of this

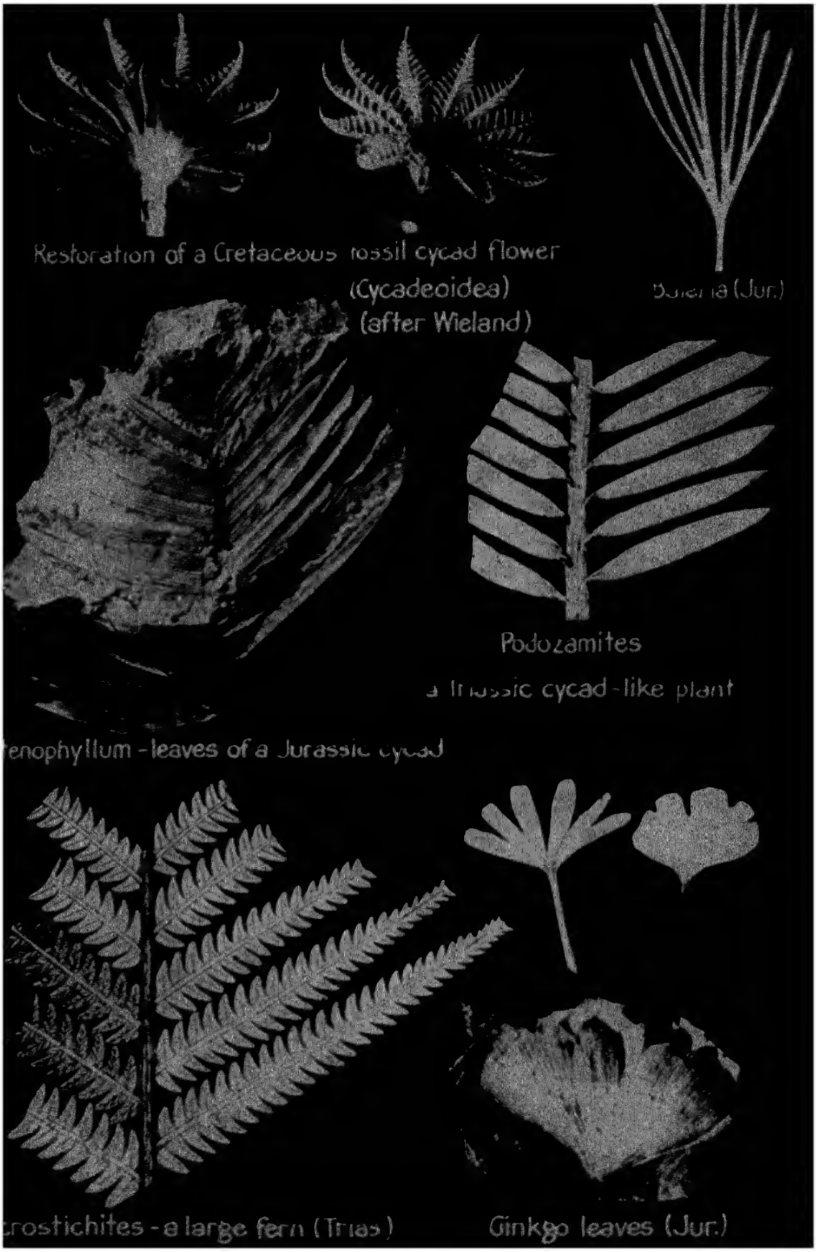

FIG. 300.—Types of Mesozoic plants.

age near Richmond, Va., and adjacent deposits, but the species are known almost solely on the basis of their leaves. One of the most abundant kinds (*Sphenozamites rogersianus*) had leaves up to 4 feet in length with lateral leaflets 8 to 10 inches long and as much as 4 inches wide. Another Triassic cycadophyte (*Ctenophyllum*), about equally common, had a similar crown of huge leaves with much narrower and more closely crowded leaflets.

The Jurassic period witnessed the rise of cycadophytes to a distinctly dominant position in the land vegetation, for approximately two-fifths of all the known plant fossils are of this type. If cycad species were relatively as numerous today, Scott points out that we should have some 40,000 different kinds instead of about 75, and that of course takes no account of numbers of individuals. The leaves show a considerable variation in shape and size, the largest being 3 feet or more in length. Unlike the short-trunked cycadophytes of Early Cretaceous time, most of those of Jurassic age had tall slender stems that were more or less branched (family *Williamsoniaceae*).

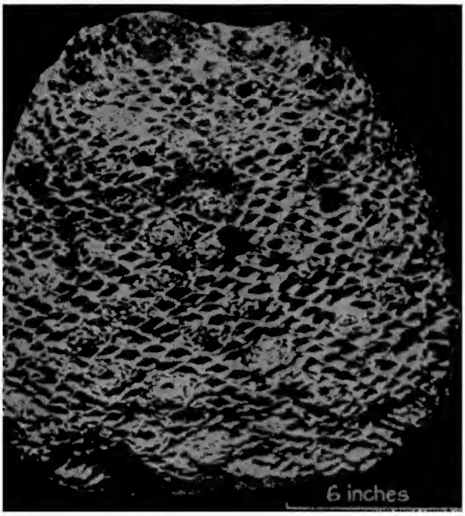

FIG. 301. A Cretaceous cycadophyte trunk (*Cycadoidea*) from Maryland. (*After Berry.*)

These were very widely distributed and fairly uniform in character. Practically the same kinds of leaves occur in the Jurassic of England, northern Greenland, Alaska, Oregon, Australia, and Antarctica.

Following the great expansion of the cycadophytes in the Jurassic period, a record no less imposing is found in the Lower Cretaceous rocks, although the nature of the fossils is mostly quite different. Instead of the numerous well-preserved leaves and rather scanty evidence of other parts of these plants in earlier Mesozoic time, the Cretaceous affords only sporadic remains of leaves but has wonderfully preserved trunks, flowers, fruits, and seeds. Even the embryo plant in the seeds has been observed. The trunks are mostly very short, about as thick as tall, the height ranging from 1 to 4 feet or occasionally more. The sides are covered by lozenge-shaped pits that mark the places of attachment of the leaf fronds. There are also numerous clusters of pits much smaller than the average, and when these are cut in section it is seen that they mark the fruits. Each fruit has a central short, stout base that bears a number of slender seed-carrying organs (pedicels) and surrounding these a circle of curiously shaped stamens with abundant pollen. The flower was thus self-pollinated. In Recent cycads the two sexes are in separate plants. This difference

and the distribution of fruiting organs over the sides of the trunk, rather than only at the top, distinguish the Lower Cretaceous cycadophytes and, with characters that separate them from earlier types, cause them to be grouped in a special family (*Bennettitaceae*). The American representatives are chiefly referred to the genus *Cycadoidea*. Specimens are principally obtained from places in Wyoming, in the Black Hills region in South Dakota, and in Maryland.

The Upper Cretaceous floras contain some cycadophytes but they are a rather inconspicuous element. For example, the Raritan beds of the Atlantic Coastal Plain have less than a dozen cycadophytes out of nearly 300 plant species, and the Dakota sandstone of the Continental Interior contains only 10 cycadophytes in more than 500 species for the entire flora. Why the robust cycadophyte stock of Lower Cretaceous times should not have persisted even to the present is hard to say, but the chief Mesozoic types declined and disappeared. They are among the most interesting plants of the earth's past.

Conifers (*Coniferophyta*)

This plant group, to which the pines, cedars, and other cone-bearing evergreens belong, and which had its forerunners in the Permian, was an

Fig. 302.—Broken sections of the trunk of a large silicified tree, a Triassic conifer, in the Petrified Forest National Monument, eastern Arizona. (*N. H. Darton, U. S. Geol. Survey.*)

important element in the floras of Mesozoic time, but the fossil record is very fragmentary and affected greatly by the nature of the local environment.

Some conifers are known from the coal basins of Triassic age in Virginia, though this moist lowland was mainly characterized by growth of cycadophytes and ferns. Triassic conifers are best known from the southwestern United States, where in the Painted Desert of Arizona and in parts of adjacent states are widely scattered fossilized trees and several "fossil forests." The most famous tree locality is an area of about 40 square miles near the town of Adamana, Ariz., which has been set aside as the Petrified Forest National Monument. Here lie thousands of fossilized logs, many of

them broken up into drum- or hogshead-like segments, others complete and unbroken. The enclosing sediments have been so removed from one that it forms a natural bridge over a ravine some 20 feet deep and 30 feet across, probably the only bridge of this sort in the world. The average diameter of the logs is 3 to 4 feet and the length 60 to 80 feet. Some logs 7 feet in greatest diameter and 125 feet long have been observed. None are standing in position of growth but, with branches stripped, lie scattered about as though rolled or floated by running water until stranded and subsequently buried in the places where they are now found. The original forests may have been scores of miles distant. The most abundant kind of tree is called *Araucarioxylon* because the wood resembles that of the modern pinelike *Araucaria*. The cell structure and fibers have been almost perfectly preserved by molecular replacement of silica, much of it in the form of chalcedony and agate that is beautiful and varied in coloring of rich yellows, red, and purples.

The Jurassic rocks in North America afford rather scanty evidence of the conifers, though several kinds are known. The fossil remains consist almost entirely of impressions of leafy twigs and branches. The conifers made up somewhat less than a third of the entire known flora.

Relative importance of conifers in number of species is about the same in the Lower Cretaceous as formerly, but they were undoubtedly the largest and most conspicuous plants of the time. There were several kinds of *Sequoia*, some very much like the giant sequoia of California, and a number of species belonging to the cypress, yew, cedar, and juniper types are known. The Upper Cretaceous conifers are less numerous and appear relatively much less important because of the rapid rise of the "broad-leaf" flowering plants—the angiosperms, especially the dicotyledons.

FIG. 303.—A large broad-leafed fern (*Macrotaeniopteris*) from the Triassic of Virginia. (*After Russell.*)

Ferns (*Pteridophyta*)

As has been noted, ferns comprise approximately one-third of the known floras of Mesozoic age, excepting the Late Cretaceous when rise of the higher plants reduces the relative importance though not necessarily the actual number of fern species.

Triassic ferns are best known in America from North Carolina, Virginia, and Pennsylvania, in parts of which region there are coal beds of Triassic age showing long persistence of very moist or swampy conditions. The Richmond coal basin in Virginia contains at least a dozen coal beds that have a combined thickness of about 30 feet. In this environment, ferns were the dominant kind of plant, and many of them were of large size. Some of the Triassic ferns are closely related to predecessors in the Late Paleozoic rocks. Several genera are distinguished on the basis of the shape and arrangement of the leaflets, their venation, and so forth. *Cladophlebis*, characteristic of the Upper Triassic and Jurassic in particular, had its beginning in the Upper Paleo-

zoic. One type (*Macrotaeniopteris*) had simple, undivided leaves that in some specimens measure 6 inches wide and 4 feet long. Another group of the ferns is regarded as including forerunners of several modern fern families, including several tropical genera, but this was not so prominent in the Triassic flora. Relatives of the now nearly extinct family Marattiaceae were comparatively abundant in both the Pennsylvanian and the Early Mesozoic floras.

The Jurassic and Cretaceous fossil ferns were all of moderate size. Locally, especially in some of the Lower Cretaceous (Patuxent) clay beds, ferns were unusually abundant, their remains forming a tangled mat in which other kinds of plants are almost absent.

Horsetails and Ginkgo

In both the swampy coal basins of the Atlantic Border and the river plains of the Southwestern Interior there are Triassic descendants (*Neocalamites*) of the Paleozoic horsetails or calamites. The ribbed stems were 4 or 5 inches in diameter and 20 to 30 feet long. This stock is also known in smaller species from the Cretaceous.

From a botanical standpoint, one of the most interesting Mesozoic plant fossils is the *Ginkgo* or maidenhair tree which was one of the most abundant and widely distributed trees during Jurassic time and which is represented today by a single species, native in China and Japan but introduced in parts of the United States and Europe. The ginkgo attains a height of 80 feet or more, has a relatively smooth trunk that in fully grown specimens may be 3 feet in diameter, and bears broad subtriangular leaves with veins radiating from the pointed base. In its peculiarly specialized method of seed fertilization, and in certain details of structure, the ginkgo evidently belongs to the *Coniferophyta*, though it stands so apart from all other plants as to constitute a distinct order. It enjoys the distinction of being probably the oldest living kind of tree, though *Araucaria*, now found mainly in the Southern Hemisphere is nearly as old, and possibly older. It has come down so little changed that it is difficult or impossible to discover differences in the fossils perhaps 45 million years or so in age and the present leaves.

The ginkgo probably originated in Late Paleozoic time, as indicated by certain Carboniferous fossils, but it is first known clearly in Medial Jurassic time, long after the araucarian stock was well established. In Oregon there are beds containing beautifully preserved ginkgo leaves by the hundreds. Jurassic deposits in Alaska, Greenland, northern Europe, and Siberia also contain them. Naturally this plant occurs in later Mesozoic and in Tertiary floras but it does not stand out so prominently as in the Jurassic when the host of modern-type leafy trees had not appeared. It became extinct in North America during the Tertiary period but, when reintroduced by man from its native habitat in China, it was found to grow luxuriantly.

Flowering Plants (*Angiospermophyta*)

The highest type of plants, dominant in modern floras, are the flowering plants, in which the seeds are inclosed in a protecting case or fruit.

Two classes are recognized: (1) monocotyledons which start with a single leaflet, lack a differentiation of the stem into pith, wood, and bark, and have parallel-veined leaves, and (2) dicotyledons, which start with two leaflets, show division into pith, wood, and bark, and have leaves with a network of veins. The first group includes the grasses, cereals, palms, lilies, and the like, while the second contains most of the forest trees such as maples, oaks, elms, and a great variety of shrubs and herbs.

The epoch in earth history which saw the first plants classifiable as angiosperms is not known. No certainly identifiable angiosperms are yet known below the Lower Cretaceous where leaves that have been referred to 16 modern families of flowering plants suddenly make their appearance. Some of these are referred to the willows, poplars, beeches,

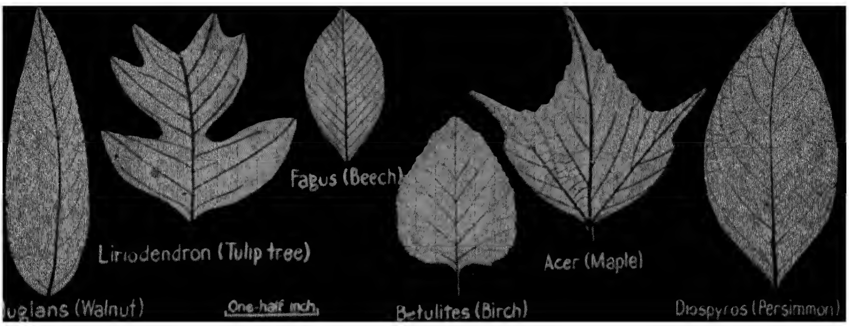

FIG. 304.—Fossil leaves of Cretaceous angiosperms.

oaks, elms, laurels, sassafras, figs, grapes, and other familiar living groups. The species are, of course, all different from those of today. In fact, some of the leaves are rather crude and undifferentiated, suggesting a rather primitive stage in development. Yet the very evident specialization and structural advancement of the later Cretaceous angiospermous floras indicate that the group must have had a considerable, and possibly a prolonged, antecedent development that is as yet almost unrecorded by actual fossil remains.

The Upper Cretaceous floras, represented by very abundant well-preserved leaves, as in the Dakota sandstone of Kansas, the Woodbine sandstone of northern Texas, the Raritan and Magothy beds of the Atlantic Coast, and various other deposits, shows a strongly dominant angiosperm content with many modern-looking elements. The Dakota flora contains more than five hundred described species. In Greenland and Alaska there are Upper Cretaceous plant-bearing beds containing conifers and hardwoods with many of the same species that occur in the central and southern part of the United States. Among them are extinct representatives of the dogwood, persimmon, fig, tulip tree, eucalyptus, sycamore, breadfruit tree, and many others that today mainly inhabit

moderately warm climates. The breadfruit tree (*Artocarpus*) is limited at present to within 20 degrees of the Equator.

SUMMARY OF LIFE DEVELOPMENT IN MESOZOIC TIME

The outstanding feature of the life of Mesozoic time is the rise to dominance of the reptiles and their radiation into almost all modes of existence on the lands, in the waters, and in the air. Chief place among the invertebrates is occupied by the cephalopods which reached at this time the culmination of their career. This is indicated by their extraordinary specialization along many lines, multitudinous variety, and the giant stature of some forms. The characteristic plant group of the era is that of the cycadophytes, though in Cretaceous time the appearance of the highest type of seed-bearing plants, the angiosperms, introduces modern aspects in the flora.

Triassic Period.—Land animals of Triassic time include the early representatives of the dinosaurs which, generally speaking, were smaller and much less specialized than succeeding forms. Footprints are common in some localities, especially in the Connecticut Valley region, but skeletal remains are rare. The Triassic rocks also contain numerous phytosaurs and the beginnings of divergent lines of marine reptiles, the ichthyosaurs, plesiosaurs, and turtles. The South African Triassic deposits show the presence of a strange group of heavy-boned reptiles (pareiasaurs) and some that are very mammal-like in certain features, especially the teeth (theriodonts). Flying reptiles are first known from rocks of Late Triassic age.

Large, heavy-skulled amphibians called stegocephalians are prominent Triassic vertebrates; the peculiar labyrinthine structure of their teeth is almost identical with that of the lobe-finned ganoid fishes. Several small jaws and teeth that have been found in Triassic rocks are classed as belonging to primitive mammals. A variety of well-preserved fishes, chiefly belonging to the ganoid (enamel-scaled) group, has been collected from the Triassic.

Among invertebrates, a great expansion of the ammonoid cephalopods in Triassic time gives special prominence to this group and inaugurates a dominance that was to continue throughout the Mesozoic era. There are almost innumerable species which, in general, show specialization of suture pattern, ornamentation, and other characters, as compared with well-advanced Permian types. Several distinctive Triassic genera of pelecypods occur but some of these are obviously related closely to Late Paleozoic predecessors. The Mediterranean region of Europe shows very thick masses of limestone composed largely of remains of corals, sponges, and algae.

Cycadophytes were well established in the Triassic period, 40 kinds being known from Virginia alone. Conifers and ferns were each about

equal to the cycadophytes in numbers. The "petrified forests" in the Triassic beds of the southwestern United States contain fossil logs 7 feet in diameter and 125 feet long, which record existence of a conifer related to the modern pinelike *Araucaria*. One of the Triassic ferns had leaves 4 feet long.

Jurassic Period.—The Jurassic period shows advancement of the reptiles along many lines. Dinosaurs approached the peak of their development in variety and size. Herbivorous types include gigantic quadrupeds, some 90 feet long and weighing in the neighborhood of 40 tons, and bipedal forms of large and small size. The strange armored dinosaur known as the stegosaur lived at this time. Ferocious carnivores existed also, but the greatest known beast of this group lived near the close of Cretaceous time. Large ichthyosaurs and plesiosaurs show very thorough adaptation to life in the sea. The former were remarkably fishlike, even in the presence of a dorsal fin and strong caudal fin; the latter resembled marine turtles in the form of flattish rounded body and powerful flippers, but they had a long neck. Flying reptiles of several varieties occur in Jurassic deposits. Here, also, appears the first known birds, *Archaeopteryx* and *Archaeornis*, which so strangely combine the characters of lizard and bird. Primitive mammals are known but are unimportant elements of the fauna.

The ammonites of the Jurassic are extremely abundant and varied, showing a very remarkable range of form, surface ornamentation, and suture pattern. The wide geographic distribution and short vertical distribution of many species provide the essentials of good index fossils, and the marine Jurassic strata have accordingly been minutely zoned on the basis of ammonites. Dibranchiate cephalopods with solid internal cigar-shaped hard parts are very abundant in some Jurassic formations; these fossils are known as belemnites. Pelecypods are fairly important elements of marine Jurassic faunas. The ornamented, subtriangular shells of *Trigonia* and the beginning of prominence of the oyster family are noteworthy. Large crinoids have been found in Jurassic beds and the five-sided stem segments of *Pentacrinus* are useful guide fossils, but the group is not very important. Portions of the Jurassic deposits of Europe are very rich in remains of corals, sponges, and brachiopods.

The cycadophytes of Jurassic time were very numerous and with fairly uniform characters were distributed throughout the land areas of the globe. Practically the same kinds of these plants are known in Europe, Greenland, western North America, Australia, and Antarctica. A prominent and botanically unique Jurassic plant is the *Ginkgo* which is represented by a living species, native to Asia.

Cretaceous Period.—The number of different sorts of reptiles of Cretaceous age is approximately equal to that of Jurassic time, but, in general, specialization along various lines had gone farther and several

reptilian types reached their peak in size. The greatest known carnivorous dinosaurs lived in the Late Cretaceous and contemporary with them were the strange horned dinosaurs called ceratopsians. The duck-billed dinosaur and others were adapted to a semiaquatic habitat, and there were some that appear to have been excellent swimmers. Plesiosaurs, ichthyosaurs, large turtles, and the great, serpent-like mosasaurs were at home in the continental seas. The largest known flying reptiles, with a wing spread of 26 feet, lived in the Late Cretaceous. Highly

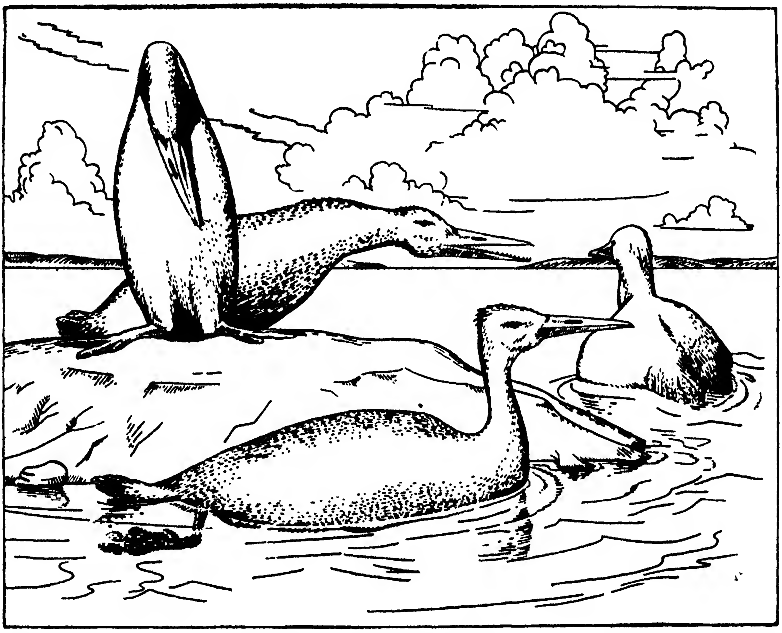

FIG. 305.—Group of *Hesperornis*, the large diving bird with teeth, that lived in the Late Cretaceous seas of western Kansas.

specialized birds, which retain reptilian characters, however, in the possession of teeth, are also known. In view of the successful adaptation of these many animals to their various modes of life, the sudden disappearance of most of the stocks at the close of Mesozoic time is interesting and puzzling.

Ammonites were abundant and varied during the Cretaceous period, and most of them are excellent guide fossils for different stratigraphic zones. The presence of several aberrant types in Upper Cretaceous formations and a decline in numbers foreshadow the extinction of the group. Pelecypods are very common and to this class belong many of the important index fossils of the system. Among the chief genera are *Gryphaea*, *Exogyra*, *Ostrea*, and *Inoceramus*. Among echinoderms the heart-shaped echinoids are outstanding in rank but there were some very interesting free-swimming crinoids. Protozoans are represented by

exceedingly abundant Foraminifera which compose a large part of chalk and some other beds.

The appearance of the angiosperms is the chief feature in the record of fossil plants of Cretaceous time. Some formations contain a very large flora of decidedly modern aspect. The short-trunked cycads of the Lower Cretaceous are prominent. Occurrence of large palms and other tropical or subtropical types in northern regions is doubtless significant of warm, genial climate in these places in Late Mesozoic time.

THE CENOZOIC ERA

CHAPTER XXVI

THE CENOZOIC FORMATIONS

Deposits of Cenozoic age are very widespread. They include marine formations, chiefly near the borders of the continents, and nonmarine deposits of fluviatile, lacustrine, eolian, and glacial origin. It is the purpose of this chapter to consider briefly the broad distinguishing characters of these youngest geologic formations, noting especially their relation to physiographic features and their distribution with respect to the older rocks that have been studied.

A chief feature of the Cenozoic formations is the general lack of consolidation, or only partial consolidation, and this is true notwithstanding the fact that some layers are tightly cemented. Hard sandstones and conglomerates occur in many places, but more commonly there are beds of sand and gravel that are only partially compacted or are not consolidated at all. Fairly resistant siliceous and sandy shales are known, but most of the silty and clayey deposits are very soft and yield readily to the attack of erosion agencies. There are compact limestones that make benches and ridges, but much the greater part of Cenozoic calcareous deposits are soft and marly. A noteworthy character of some formations is the occurrence of hard concretionary masses, generally rounded in form, and a foot or more in thickness. These are embedded in soft shale or sand.

A prominent feature among sedimentary deposits of Cenozoic age is the extremely widespread occurrence of glacial deposits in the Northern Hemisphere. Igneous formations, consisting of granite, porphyry, and various other sorts of intrusive rocks, and comprising also a great variety of extrusive materials, are especially important in western North America and parts of other continents.

Partly as a result of the geographic location and mode of origin of Cenozoic sedimentary deposits and partly because of their average lack of resistance to erosion, these formations occur commonly in lowland plains. Chief of these are the coastal plains. Exceptions to this generalization are found in some of the deposits capping high plateaus, as in parts of western North America, and especially in igneous formations that occur in parts of high mountain areas. The topography of parts of these regions is extremely rugged. The great elevation of some Cenozoic rocks above sea level is due mainly to recent movements of the earth crust that have elevated the plateau and mountain regions by thousands of feet.

CENOZOIC FORMATIONS OF NORTH AMERICA

Atlantic Coastal Plain.—Cenozoic formations comprise the outer portion of the Atlantic Coastal Plain from the vicinity of New York

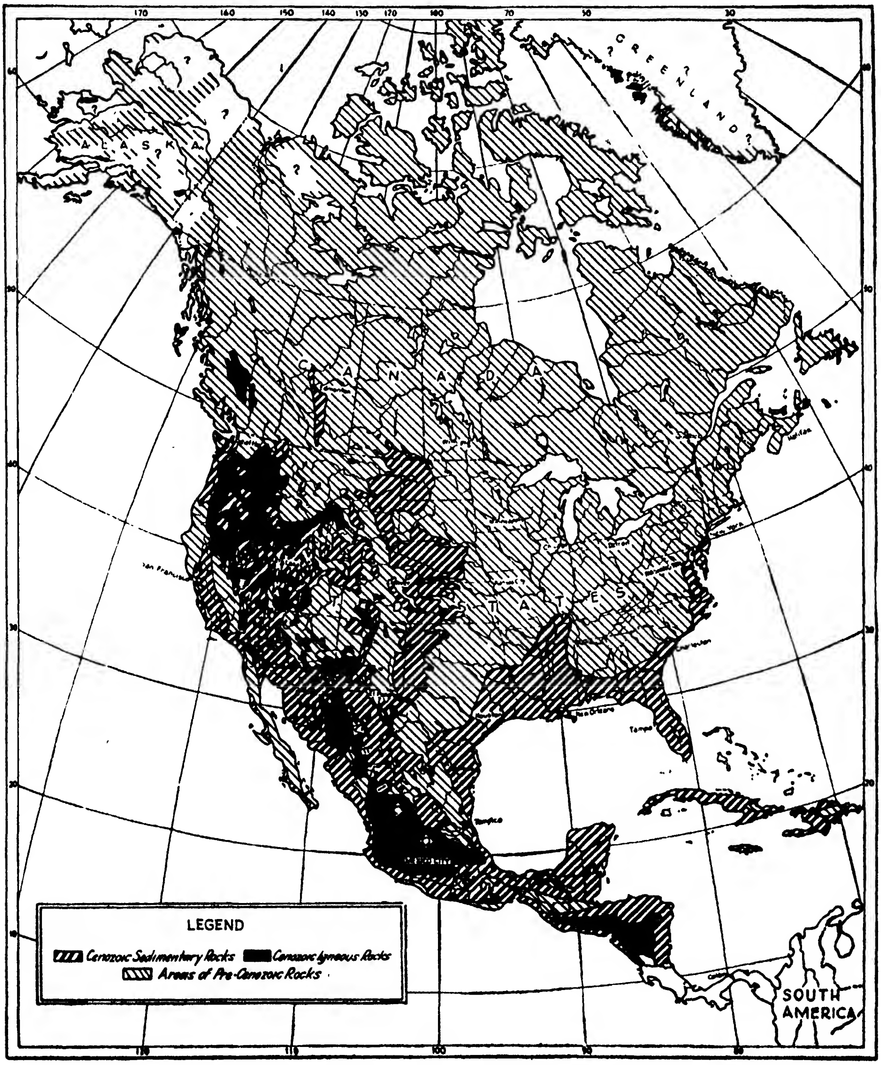

Fig. 306.—Map of North America showing outcrop areas of Cenozoic formations.

City southward. They rest disconformably on Mesozoic rocks, which make the inner part of the Coastal Plain, or in places overlap on older formations. The width of the Cenozoic belt exceeds 100 miles in some places and it comprises all of the Florida Peninsula. The beds dip gently seaward. The land surface also slopes very gently seaward and

in many places resembles a smooth or gently undulating sea floor. Some of the harder formations make cuestas, with the steep slopes facing inland. Most of the streams are small and the valleys shallow. The interstream areas are mostly wide, nearly flat, and in places swampy. Tidal estuaries and salt marshes are common along the coast, and elongate barrier beaches with a covering of sand dunes are a common feature.

Much of the Coastal Plain belt is tree-covered, the long-leaf pine being one of the most common trees in the part of the Plains occupied by Cenozoic formations. Bottomlands, especially along some of the

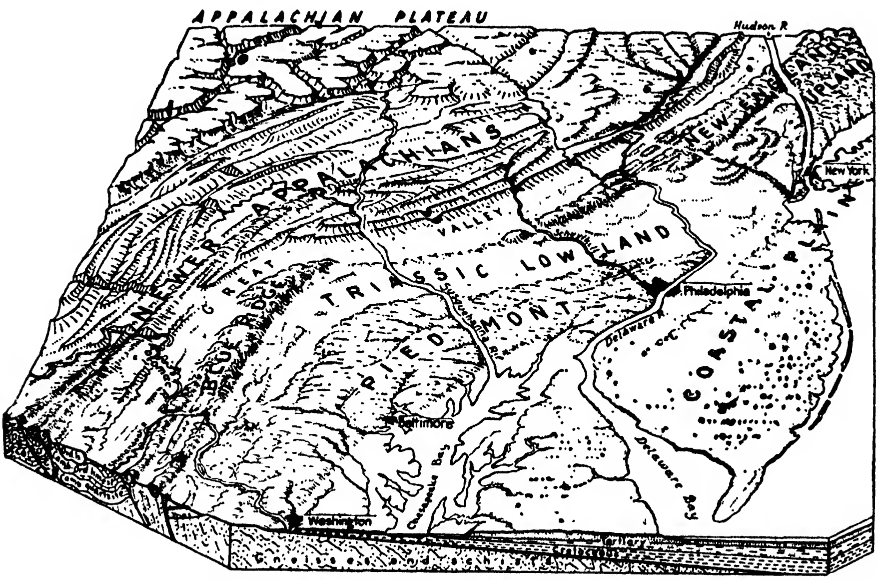

FIG. 307.—Block diagram showing relations of the Coastal Plains formations to older rocks. (*D. W. Johnson, International Geol. Congress Guidebook* 7. *Drawn by E. J. Raisz.*)

larger streams, are densely forested, and swamps, especially toward the south, contain thick growths of cypress.

The Florida Peninsula, which projects some 350 miles southeastward into waters of the Atlantic Ocean and Gulf of Mexico, is mostly less than 100 feet above sea level. The northern and western parts of Florida consist of a narrow limestone upland in which the rocks are of Early Cenozoic age. The southern and central portions of the peninsula are a great lake and swamp district, the lakes occupying depressions or sinks in the underlying limestone, or occurring in shallow cavities that are due to irregularities in the comparatively recently elevated sea floor. Underground drainage through the porous limestone formations is common. Sinks and springs are very numerous, the latter including some of the largest features of this sort known in the United States.

Gulf Coastal Plain.—The geologic structure and topography of the Gulf Coastal Plains region are essentially similar to the plains of the Atlantic Border, but the Gulf Plains are broader, attaining a maximum width of more than 500 miles near the Mississippi. The Cenozoic formations have an average dip of 30 to 40 feet to the mile toward the Gulf. The surface of the land slopes in the same direction, but at a much less rapid rate, averaging about 1 foot per mile. Accordingly, in travel from the inner border of the plain toward the coast one successively crosses the beveled edges of the Cenozoic deposits from oldest to youngest. The width of outcrop of each formation is approximately proportional to its thickness. Some of the sandstone and limestone formations make cuestas, with steep landward-facing slopes and very gentle seaward slopes. The outcrops of weak calcareous formations are commonly marked by smooth-contoured, poorly drained valleys. These features are typical of the so-called Black Prairies.

The main streams of the Coastal Plain flow nearly at right angles across the outcrops of Cenozoic formations. These are consequent streams, the courses of which were established with reference to the gentle seaward-sloping surface of the emerged former sea bottom. The tributary streams, on the other hand, mostly follow the trend of the rock outcrops, depressions being carved especially in the weaker strata. These streams are subsequent and they join the master valleys at nearly right angles.

Parts of the plains area, especially certain low ridges, are wooded. Other parts are open prairies or savannas clothed with coarse grass and locally dotted with scrub pine or palmetto. Along much of the coast are wave-built ridges or reefs, some of which on the Texas coast are remarkably long and continuous. Behind the sand reefs are lagoons, irregular estuaries, and reedy swamps.

The Mississippi Valley, south of the mouth of the Ohio, is a vast alluvial plain that lies practically at base level. Its materials are Cenozoic deposits of recent origin. The eastern and western borders of this district are defined by lines of bluffs. The river plain has a scarcely perceptible slope southward, and the maze of bayous, lakes, and abandoned channels show that the surface is very ill-drained. The southern portion of the plains, part of which is extended to form the Mississippi Delta, is barely above tide level, and along the coast are permanent tidal marshes. A large part of the swampy bottom lands are covered by heavy forests of cypress and gum.

Interior Plains Region.—The Great Plains country east of the Rockies, the central and upper Mississippi Valley region, the territory surrounding the Great Lakes, and great areas in the north central part of the continent contain thin but very extensive deposits of Cenozoic age. The relation of these to important topographic characteristics of

these regions is especially noteworthy. The Great Plains slope very gently eastward, the western portion in many places being more than a mile above sea level. Most of this area is a treeless prairie, a gently rolling or in places almost perfectly plane surface that in the natural

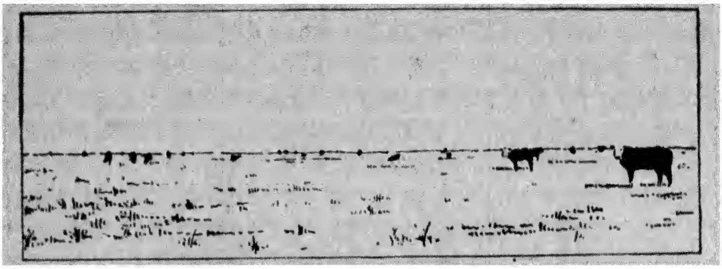

FIG. 308.—A part of the High Plains of western Kansas near the Colorado boundary. Much of this country, in which Pliocene deposits occur next below the soil covering, is a featureless plain.

state bears a covering of short grass. Formerly, this was the range of countless herds of buffalo. Now, this country is employed for cattle grazing and wheat growing. Sand-dune areas, many square miles in extent, occur in some parts of the region. The eastern border of the

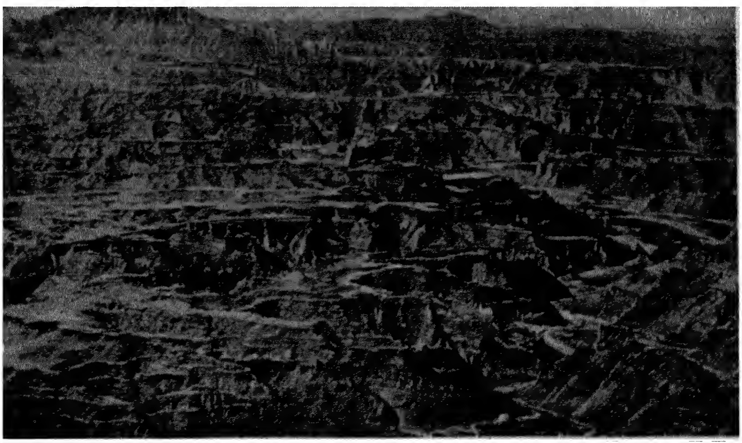

FIG. 309.—The Badlands of South Dakota, an intricately dissected part of the weak Cenozoic sedimentary deposits of the Great Plains region. (*N. H. Darton, U. S. Geol. Survey.*)

Cenozoic deposits in parts of Texas, Oklahoma, and Kansas is marked by a prominent escarpment, called "the break of the plains."

The northern Mississippi Valley, Great Lakes region, and territory in Canada extending far to the north is mantled by glacial deposits belonging to the latter part of Cenozoic time. Throughout much of the area, these deposits fill in irregularities of the underlying bedrock, producing a very flat or a gently rolling land surface. Elsewhere there are

belts of hummocky topography representing moraines, and especially in the north there are innumerable lakes and marshes. At the border of the Great Lakes in several places, and covering a large territory in North Dakota, Manitoba, and eastern Saskatchewan, are flat plains that represent the bottom of former lakes. Beach ridges are prominent at the borders of the ancient lake beds in many places and are traceable for scores of miles. Thick deposits of loess occur on the uplands bordering large streams. Thus, the topographic characteristics of this large territory are mainly traceable to the nature of Cenozoic deposits in the region. The making of the Great Lakes belongs to the Cenozoic era.

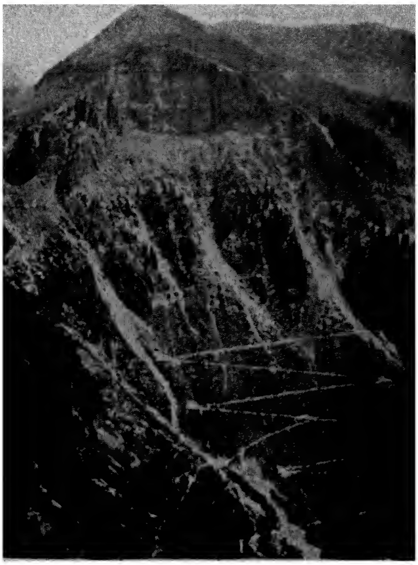

Fig. 310.—Part of the San Juan Mountains near Telluride, Colo. The San Juans are mainly built of a huge mass of Cenozoic volcanic rocks. They contain important deposits of metals. (*W. T. Lee, U. S. Geol. Survey.*)

Rocky Mountains.—The Rocky Mountains province, which may be defined to include the mountain and plateau country between the mountain front on the east and the Great Basin on the west, contains a variety of Cenozoic deposits. Besides glacial, fluviatile, and other deposits of mountain valleys, thick sedimentary formations occur in several of the intermontane depressions called "parks," and in broad synclinal areas such as occur in northwestern New Mexico, northeastern Utah, and in central Wyoming. Sedimentary and igneous formations of Cenozoic age cap the High Plateaus in Utah and form the summit portions of the San Juan Mountains in southwestern Colorado. Cenozoic granites and other intrusive igneous rocks form mountain peaks in other parts of this district. Upwarping of the region and very extensive

erosion during Cenozoic time are chiefly responsible for the present topographic characteristics of the mountain belt.

Great Basin.—The Great Basin region contains numerous north-south-trending mountain ranges that are separated by broad desert valleys. Cenozoic formations, consisting chiefly of fluviatile and lacustrine deposits, occur in the valleys. Chief topographic characteristics of the valley areas are the long gentle slopes of piedmont alluvial fans and the flat surface of playa or lake deposits in the central part of the intermontane basins. Shore-line features of formerly extensive lakes are prominent in places, as near Salt Lake City.

Pacific Border.—Most of the exposed sedimentary formations in California, Oregon, and Washington are of Cenozoic age. Their aggre-

FIG. 311.—Vertical Tertiary beds on the California coast, San Mateo County. (*Ralph Arnold, U. S. Geol. Survey.*)

gate thickness in many places is measured in tens of thousands of feet, and most commonly the beds are found tilted at various angles. Locally the strata are vertical or form parts of overturned folds. Lava flows cover thousands of square miles in the Columbia River area in eastern Washington, Oregon, California, northwestern Nevada, and southwestern Idaho. Crustal movements of Cenozoic time produced the Sierra Nevada, Cascade, and Coast Ranges and the work of erosion in Recent geologic time is mainly responsible for the scenic characters and topographic diversity that distinguish this region.

CENOZOIC FORMATIONS OF OTHER CONTINENTS

Europe.—Marine and nonmarine deposits of Cenozoic age are extremely widespread in Europe. The marine formations occur chiefly in the vicinity of London, in the central part of the Paris Basin, southwestern France, northern and southern Spain, Italy, southern Germany, Belgium, the Carpathian region, and southeastern Russia. These rocks are thickest and consist most largely of limestone in the Mediterranean region. Nonmarine deposits, including especially widespread glacial drift of Quaternary age, occur in Germany, Denmark, Poland, and northern Russia.

Dominantly, but not altogether, the Cenozoic formations occupy the lowland plains of the continent. The prominent mountain ranges of Europe were chiefly formed during Cenozoic time, but the rocks exposed in the mountain areas are chiefly older than Cenozoic. The general topography and the outline of the European continent are almost wholly an expression of conditions and events belonging to comparatively recent geologic time. Volcanic activity was pronounced in parts of northwestern and southern Europe, volcanoes of the Mediterranean district being still intermittently active.

Asia.—Cenozoic formations of the Asiatic continent include marine limestones and other deposits of the Himalayan belt extending from Asia Minor to Burma, and

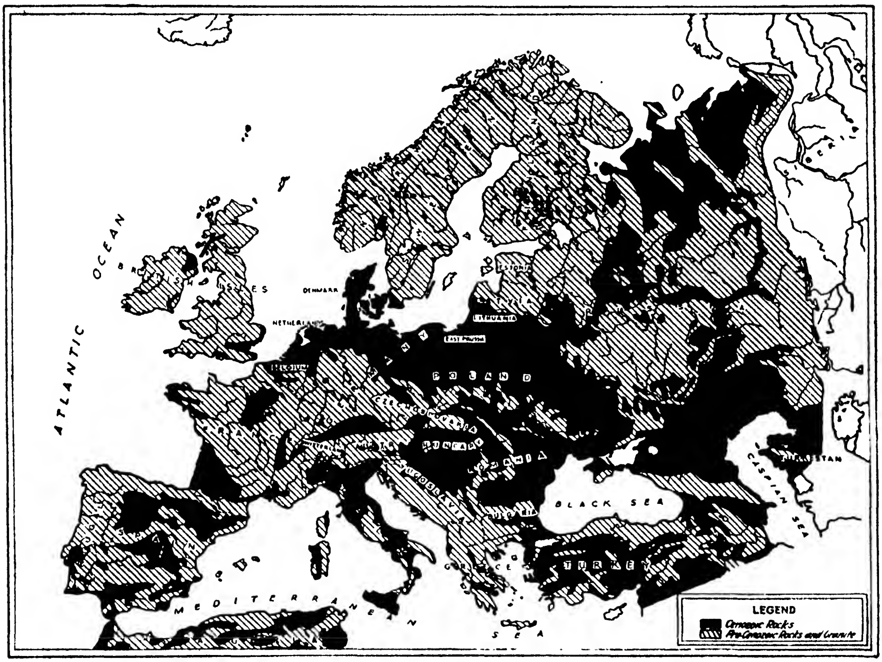

FIG. 312. Map of Europe showing outcrop areas of Cenozoic formations.

there are also locally thick and very widespread nonmarine deposits, chiefly of fluviatile and lacustrine origin. Some of the deposits on the south flanks of the Himalayas in northern India and in the Gobi Desert region of Mongolia have yielded rich remains of land vertebrates. The loess deposits of northwestern China and adjacent territory are one of the chief examples of this type of eolian deposits in the world. The broad alluvial plains and deltas of the Ganges, Yangtze, and Hwang Ho occupy thousands of square miles and support the densest population of any part of the globe. The Himalayas and other lofty mountain ranges of the continent were formed in Cenozoic time.

Australia.—Sedimentary and volcanic rocks of Cenozoic age are well developed in Australia, being chiefly found in the southern and southeastern parts of the continent.

The sedimentary and volcanic rocks of most of the East Indies and the islands of Oceanica are of Cenozoic age.

Africa.—Marine formations of Cenozoic age occupy much of northern Africa, and they are found to some extent in western Madagascar. Continental deposits con-

taining fossil bones are known in Egypt. Desert sands and river deposits, as in the plain and delta of the Nile, are very recent deposits that cover a large area.

South America.—Cenozoic formations in South America are most widespread in Argentina, Bolivia, and the upper Amazon. Deposits of considerable thickness but small areal extent occur in Venezuela and along parts of the Pacific Coast. The great elevation of the Andes mountain chain and the occurrence of much volcanic activity in this region are features of Cenozoic history.

SUMMARY

The Cenozoic formations are mainly unconsolidated marine and nonmarine deposits. In North America they comprise the outer portion of the Atlantic and Gulf Coastal Plains and they form the covering of a large part of the High Plains region east of the Rocky Mountains. Nonmarine sedimentary formations, that are locally of great thickness, and volcanic deposits occur in many parts of the mountain and plateau country of western North America. Cenozoic deposits of the Pacific Border are very thick and are mainly marine. A relatively thin cover of glacial deposits extends over much of the northern part of the continent.

Cenozoic deposits are widespread and prominent in all of the other continents.

Almost all features of existing landscapes have their origin or owe distinctive characters to conditions and processes of Cenozoic geologic history.

CHAPTER XXVII

FORMATIONS AND PHYSICAL HISTORY OF TERTIARY TIME

The Cenozoic era, or era of "recent life," comprises two geologic periods of very unequal time value, the Tertiary, which is relatively long, and the Quaternary, which is short. The names Tertiary and Quaternary are an inheritance from the early days of geology when the rocks were grouped in four time divisions. Although the Tertiary is in no sense "third," the term is so firmly fixed in geologic writing that it will probably always remain.

Definition and General Character.—The base of the Tertiary system is defined in most places by an unconformity. The marine faunas of the Early Tertiary and Late Cretaceous are very distinct, as are also, in general, the remains of land life. Determination of the precise Cretaceous-Tertiary boundary in western North America is a problem, however, that was discussed in the chapter on the Cretaceous.

The top of the Tertiary is marked by changes in marine and nonmarine sedimentation associated with the advent of glacial climate in the latter part of Cenozoic time.

The Tertiary formations are broadly distinguished by the unconsolidated or partially consolidated nature of the sediments. This does not mean that hard rocks are lacking, for there are tightly cemented beds among both the land deposits and those formed in the sea. Resistant strata are very much less prominent on the average, however, than in older systems. Much of the low coastal plains on the eastern and southern sides of the continent, and to a lesser extent on the west, is composed of these weak rocks.

The marine Tertiary formations include shale, sandstone, and limestone or marl. The shale beds are mostly sandy or clayey in character and are commonly bluish or other dark color. They are very soft and easily eroded, except in a few cases such as parts of the Pacific Coast Miocene siliceous shale (Monterey). The sand deposits are mostly rather impure and silty, lenticular, or grading laterally into shale. Some of the limestone formations are fairly hard and dense, some are coquina-like masses of shell fragments, and some are soft earthy marls. The logs of deep wells drilled in the Tertiary strata of the Gulf Coastal Plain commonly record "boulders," which are hard thin beds or concretionary masses in the soft sediments. A prominent type of sediment in parts of the marine Tertiary deposits is glauconite or greensand, a

ferrous aluminum silicate that is deposited on the sea bottom in small rounded grains, often identifiable as the filling of minute foraminiferal shells.

The nonmarine Tertiary is made up of shale, sandstone, conglomerate, coal, and fresh-water limestone. In addition there are great thicknesses of wind-blown and water-laid volcanic materials—tuffs, agglomerates, ash beds, and the like. The shaly deposits vary widely in lithologic characters, thickness, and areal extent. Like the conglomerate and much of the sandstone, a majority of the shale beds are fluviatile in origin. Lake-deposited shale, distinguished by even bedding and uniformity of character over a considerable territory, also occurs in the

FIG. 313.—Delicately tinted and fantastically carved early Tertiary rocks (Wasatch) in Bryce Canyon, Utah. (*G. L. Beam, National Parks Association.*)

Tertiary formations of the Continental Interior. Some of the sandstone beds are clearly channel fillings and stream-borne sheets or lenses; others are very irregularly cross-bedded wind-blown sands. The thickness of sandstone is measured locally in scores of feet. Coal beds are numerous and extensive in parts of the Tertiary. The plant material is less changed than in most of the older coal deposits, and most of the beds may properly be called lignites. Limestone is not abundant in the nonmarine Tertiary but there are a few lake beds consisting of fairly pure limestone. Also, calcium carbonate is a prominent constituent or cementing material of some of the Tertiary deposits of the High Plains, forming the so-called "mortar beds." Volcanic sedimentary materials are most abundant in some of the mountain areas, like the San Juan region of southwestern Colorado, where there was great volcanic activity during this period.

Classification.—The main divisions of the Tertiary rocks are established on studies of the deposits in western Europe. Very fossiliferous partially consolidated strata that are in part marine and in part nonmarine occur there in a gentle structural basin. The alternation of the two types of deposits makes possible a precise correlation of changing characters of the marine faunas with the similarly changing land plants and animals. There are also physical and faunal breaks in the succession of these strata that have led to recognition of four series, named in order from oldest to youngest (1) *Eocene,* (2) *Oligocene,* (3) *Miocene,* and (4) *Pliocene.* These names were intended to indicate the proportion of modern species of marine invertebrates that is found in the fossil faunas. Thus, Pliocene means "more recent," indicating that a majority of the fossils belong to living species; Miocene means "less recent," Oligocene, "few recent," and Eocene "dawn of the recent." This scheme of nomenclature, devised by the great English geologist Charles Lyell, is less desirable than the use of geographic names, but here again long usage gives standing. There is a much closer approach to modern species in the Pliocene than in older divisions of the Tertiary but critical study reveals differences in Pliocene and Recent species that are of decided stratigraphic value.

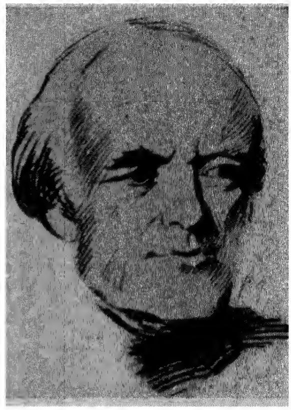

FIG. 314.—Sir Charles Lyell (1797–1875).

Study of the transitional deposits that largely connect the Mesozoic and Cenozoic has led to introduction of the term *Paleocene* for certain beds that are distinguished by the very primitive character of their fossil mammals. Since an important unconformity separates the Paleocene from overlying Eocene strata, the former should possibly be assigned rank as a series like the latter.

From some angles it is convenient and desirable to divide the Tertiary into two major parts, an older and a younger. The older division, including Paleocene, Eocene, and Oligocene, is thus called *Eogene,* and the younger division, including Miocene and Pliocene, is called *Neogene.*

As in the case of each of the older geologic systems, there are very many local stratigraphic units to which geographic names are applied. To some extent these are combined in groups of formations, and the groups in turn compose series, but the serious student of Tertiary deposits is confronted by a bewildering array of formation names.

TERTIARY FORMATIONS OF NORTH AMERICA

The Tertiary formations of North America may be grouped broadly in three regional divisions (1) the Atlantic and Gulf Border, including

most of the Coastal Plain from New Jersey to Yucatan and part of the West Indies, (2) the Western Interior, comprising most of the High Plains and many parts of the mountain and plateau country farther west, and (3) the Pacific Border, including chiefly outcrops in California and western Oregon and Washington. The first of these geographic divisions is distinguished by prominence of marine deposits containing an Atlantic

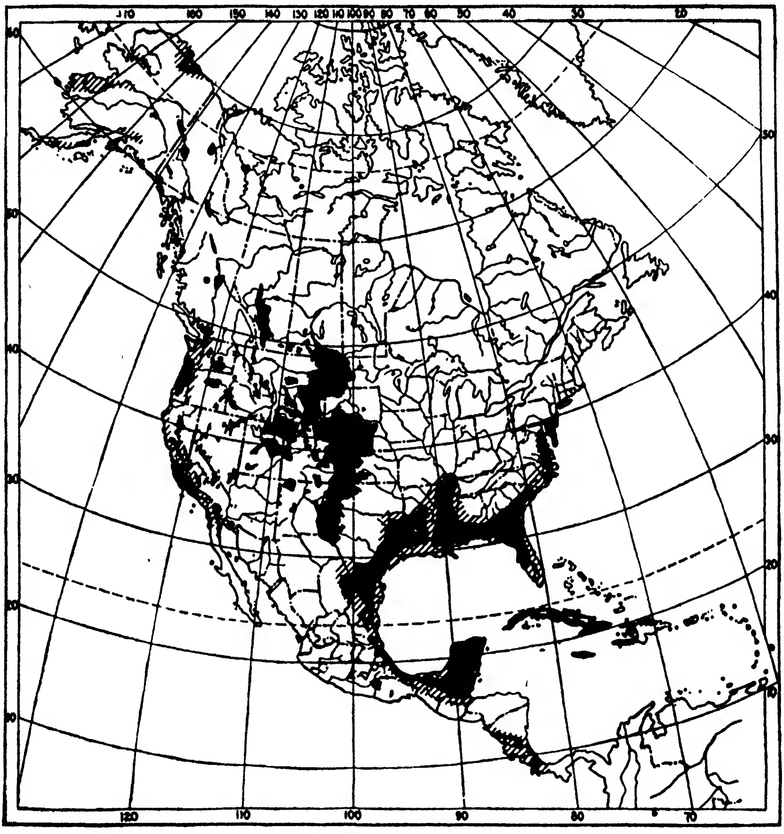

FIG. 315.—Map of North America showing outcrop areas of Tertiary sedimentary formations (black) and the inferred area of original distribution of Tertiary sediments (oblique shading) including territory in which Tertiary beds are concealed by Quaternary deposits. (*V. R. D. Kirkham, in Chamberlin and Salisbury's Historical Geology, Henry Holt & Company.*)

fauna; the second consists exclusively of continental deposits; and the third contains marine formations that carry faunas of Pacific origin. Nonmarine beds occur in the Tertiary of the east and west coasts but they are subordinate to the marine strata.

A vast amount of igneous rock of Tertiary age is found in western North America (Fig. 329),

Atlantic and Gulf Border

The northeasternmost outcrops of Tertiary rocks in North America appear in islands off the southern New England coast. The Coastal Plain composed largely of Tertiary sediments formerly extended much farther north than now, for soundings in the Gulf of Maine and on the Grand Banks indicate the existence of submerged landfacing cuestas, and dredgings have brought up Tertiary fossils. Beginning in east central New Jersey, the Coastal Plain becomes gradually wider southward. It occupies nearly half of Georgia and Alabama, all of Florida, all but the northeastern corner of Mississippi, and reaches northward to southern Illinois. West of the Mississippi River the inner border of the plain trends rather regularly southwestward across central Arkansas and Texas into Mexico. The width of the plain ranges from about 150 to 400 miles. South of the Rio Grande the plain is narrow except in Yucatan. Much the largest part of this extensive lowland, 3,000 miles long, is composed of Tertiary formations and the area of Tertiary exposures is almost unbroken from one end of the plain to the other. The Tertiary underlies all but the inner edge of the Coastal Plain, which is composed of Cretaceous rocks. In many places on the seaward side and along the Mississippi Valley the Tertiary beds are concealed by Quaternary deposits.

The thickness of the Tertiary strata of the Atlantic and Gulf Coastal Plain ranges up to an estimated maximum in the Mississippi embayment of about 30,000 feet. The average total thickness probably exceeds 3,000 feet, but because of the great variation in different regions this figure is only a rough approximation. Since practically all of the Tertiary sediments of the Coastal Plain were deposited near sea level, the fact that thickness is measured in thousands of feet means that slow subsidence has affected the margin of the continent as sedimentation proceeded.

The structure of the plains formations is simple. The beds dip seaward at a very gentle angle, mostly about 20 to 30 feet to the mile. The older Tertiary rocks are slightly more steeply inclined than the younger, which means that the thickness of the Tertiary is greater near the sea than at the outcrop. It is undoubtedly true, however, that this divergence between lower and upper stratigraphic horizons does not continue indefinitely, for each Tertiary formation and the Tertiary as a whole must become thinner at a distance from land. The cross-sectional form of the Tertiary deposits, which would be revealed by a vertical cut at right angles to the strike, may be pictured as a great lens that is thickest at some intermediate point between the landward margin and the thin seaward continuation in the oceanic oozes.

The Coastal Plain Tertiary formations consist partly of marine and partly of nonmarine deposits. The former are shallow-water muds, sands, and limestones and their presence far inland from the modern coast line shows that the continent was less extensive during most of Tertiary time than now. The nonmarine sediments consist chiefly of river-laid clay, silt and sand, and swamp beds. Deltaic materials are especially prominent in the Mississippi embayment. Deep drilling in parts of the plains has shown the existence of marine beds that are

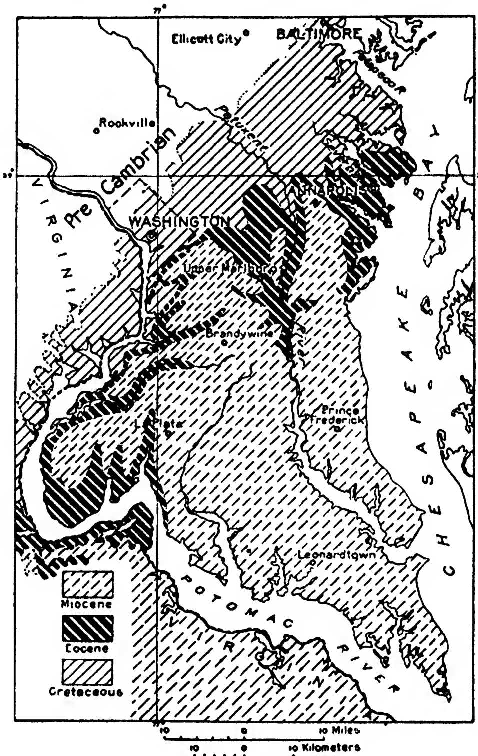

FIG. 316.—Geologic map of a part of the Atlantic Coastal Plain near Washington, D. C., showing Cretaceous beds at the inner margin of the plain, a belt of Eocene rocks east of the Cretaceous area, and Miocene deposits covering a large territory toward the Atlantic. (*C. W. Cooke, U. S. Geol. Survey.*)

equivalent to nonmarine formations at the outcrop; that is, the exposed continental sediments grade into or interfinger with contemporaneous marine sediments in a seaward direction.

Eocene Formations.—Beds of Eocene age are found from one end of the Coastal Plain belt to the other. They rest with well-defined unconformity on Cretaceous rocks, or locally on folded, erosion-beveled Paleozoic or pre-Cambrian crystalline rocks. The outcrop of the Eocene formations occurs at the inner margin of the Tertiary belt, forming a band parallel to and between the outcrop belts of the Cre-

taceous and younger Tertiary. The northern part of the Atlantic Coastal Plain—that is, north of South Carolina—contains only disconnected Eocene outcrops because the Miocene overlaps and entirely conceals the Eocene in several places. The discontinuity of the outcrop does not at all mean that Eocene formations are lacking beneath parts of the plain that lie seaward from the breaks in the Eocene outcrop belt. From South Carolina the Eocene may be followed in a broad belt southwestward, westward, and then northward to the southern tip of Illinois. An extension occupying most of northwestern Florida is the central part of a broad anticline, the west flank of which is submerged by the Gulf of Mexico. Along the Mississippi, fluviatile deposits of Recent age conceal the Eocene in an area amounting to several thousand square miles, but across southern Arkansas, northwestern Louisiana, and southeastern Texas the Eocene outcrop is a broad band up to 150 miles in width.

The Eocene of *Maryland and Virginia* consists chiefly of glauconitic greensands and marl beds (Pamunkey) a little over 200 feet thick. These deposits belong to the early part of the epoch.

The *southern Atlantic and Gulf* Eocene is divided into four groups. (1) The lowermost (Midway) consists of marine limestone or marl and some clayey and sandy beds, the total thickness ranging from about 150 to 400 feet. Some layers contain abundant well-preserved fossils. (2) The second group (Wilcox) is made up mainly of continental sediments, coarse to fine, generally cross-bedded sands, sandy clays, and light or dark pure clays. The name "lignitic" was formerly used for this group because of the common occurrence of lignite beds, some of which are 8 feet thick. The thickness of the whole group ranges from less than 100 feet to nearly 2,000 feet, the average being around 500 feet. A large number and variety of well-preserved leaves of land plants occur in this part of the Coastal Plains Eocene. Marine strata containing numerous fossils also belong here. (3) The third group (Claiborne) is essentially marine. At the type locality in Alabama the formations belonging here consist largely of sandy materials, 300 to 500 feet thick. Glauconite is prominent and in places deposits of brown iron ore have been formed by its decomposition. Some beds are composed mainly of oyster shells and some are famous for the great number, variety, and beautiful state of preservation of their marine fossils. The occurrence in eastern Georgia and South Carolina of strata belonging to this upper-middle part of the Eocene directly overlying Cretaceous and pre-Cambrian rocks shows that the Atlantic extended farther inland at this time than previously in the Tertiary period. West of the Mississippi, the beds assigned to the Claiborne group include nonmarine lignitic clays and sands; glauconite, limonite, and locally iron ore are prominent; and the total thickness increases in places to more than 1,000 feet. Well-

preserved marine fossils are found in many places but they hardly rival those from Alabama. (4) The uppermost Eocene group (Jackson) is typically developed in Mississippi. The outcrop, 10 to 30 miles wide, forms the so-called "central prairie" which extends eastward across Alabama. The deposits consist of marl and clay beds, with sand in places at the top; concretionary limestone masses are common locally. This part of the Eocene is mainly marine. The thickness ranges up to 550 feet. An extension of these rocks southeastward occupies a large area in northern Florida and well records indicate that it probably underlies the entire peninsula.

Oligocene Formations.—The Oligocene consists of beds that are classed together as the Vicksburg group. The formations are very well exposed in the Mississippi River bluffs near Vicksburg and outcrops are traced eastward as far as South Carolina and Florida. The Oligocene is lacking in the northern Atlantic plain. The deposits are marine and some beds abound in well-preserved fossils. The faunas are rather sharply distinguished from those of the series below and above and are sufficiently similar to Oligocene faunas of the West Indies and Europe to make correlation fairly definite. Unconformities and overlaps indicating crustal movements and considerable shifting of the sea in parts of the Coastal Plains region serve further to differentiate the Oligocene strata. The marine Oligocene does not extend far west of the Mississippi at the surface but is penetrated in wells in eastern Texas. The thickness of this series is mostly less than 300 feet.

Miocene Formations.—Deposits of Miocene age form the surface of most of the northern part of the Atlantic Coastal Plain, that is, from east central North Carolina to Long Island. Farther south, however, in South Carolina and Florida, Miocene outcrops are restricted to a few small, disconnected areas. Beginning in western Florida, the belt of Miocene outcrop may be followed almost continuously westward and southwestward into Mexico. On the side of this belt toward the Continent Interior are exposures of Oligocene strata and on the side toward the Gulf are Pliocene beds.

The *northern Atlantic Coastal Plains* Miocene is best developed in the vicinity of Chesapeake Bay. The deposits consist of marine sands, clays, and marls which rest unconformably on Eocene or locally on pre-Tertiary rocks. Formations are differentiated on the basis of distinctive faunal content, disconformities, and to some extent on lithologic characters. The beds are classed together under the name Chesapeake group. The total thickness ranges from about 400 to 600 feet but northward in New Jersey the Miocene is only 200 feet or less. Fossils are very abundant in some beds.

The *southern Atlantic Coastal Plains* show Miocene deposits that differ in various ways from those in the Chesapeake region. The for-

mations are limestones or marls that contain a distinctly warmer-water fauna than is found in the north; the outcrop areas are small scattered patches; the thickness, except in Florida, is less than 100 feet; and the Miocene rests disconformably on Oligocene. In eastern Florida the Miocene consists of porous or hard, dense limestone and siliceous clay that attains a thickness of 500 feet. Although exposures of this limestone are not extensive, the formation extends beneath younger deposits to the southern tip of the peninsula.

The *Gulf Coastal Plains* contain both marine and nonmarine Miocene beds. The western Florida deposits consist of limestone, soft calcareous

FIG. 317.—Outcrop of very fossiliferous Miocene siltstone (Calvert) on Patuxent River Md. (*N. H. Darton, U. S. Geol. Survey.*)

sand, and clay about 250 feet thick but increasing in thickness westward. The Miocene of southern Mississippi appears to represent estuarine sedimentation. West of the Mississippi River no outcrops of marine Miocene are known, although many deep wells in southern Louisiana and southeastern Texas encounter thick marine strata of this age. The continental Miocene formations consist of cross-bedded coarse gray sands with local lenses of clay and conglomerate and are evidently of fluviatile origin mainly.

Pliocene Formations.—Deposits of Pliocene age include (1) fossiliferous marine marls near the coast in North and South Carolina and in Florida, and (2) thin but extensive nonmarine deposits consisting (*a*) of clays, sands, and gravels that cover interstream areas of a large part of the southern Coastal Plain, and (*b*) of the Florida pebble phosphate beds. The nonmarine materials range in thickness up to 200 feet but generally they are less than 25 feet. The unconformity at the base is very prominent.

Salt Domes.—A peculiar structural feature of the Tertiary plains in Louisiana, Texas, and Mexico is the occurrence of several scores of

cylindrical pluglike masses of salt that penetrate the Tertiary strata from below. These salt masses are a mile or more in diameter, the sides are practically vertical, and the flat, rounded, or conical top is capped by a varying thickness of anhydrite, gypsum, limestone, and in some places sulphur, which form the so-called "cap rock." In a few cases the salt reaches almost to the surface, which bulges upward in the form of a rounded hill above the salt or, on the contrary, where solution is

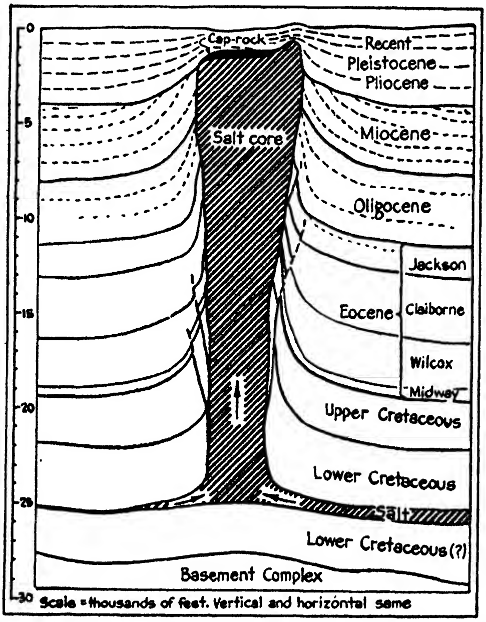

FIG. 318.—Diagram representing structural relations of a Louisiana salt dome, based on evidence of deep wells in many areas, showing that the source of the salt is stratigraphically lower than at least the upper part of the Lower Cretaceous series. (*Modified from H. V. Howe.*)

active, sags downward, forming a shallow brine-filled saucer. Drilling of wells on and around many of the salt plugs has shown that the Tertiary beds are faulted and folded upward in a zone surrounding the salt. The deeper, older beds are more steeply tilted than the shallower, younger strata. It is known that the salt must come from a widespread, deeply buried source of pre-Tertiary age and it is clear that the upward movement of the salt is a result of pressure that causes the relatively mobile salt to flow in the direction of least resistance, which is toward the surface. The cause of the pressure is believed to be simply the weight of the sediments overlying the salt bed. The mechanism of the salt flowage is analogous to that of glacial ice, which requires only gravitative pressure of a sufficient snow and ice thickness, or of rock flow, which requires great differential earth pressures. The location of the salt

domes is probably controlled by places of structural weakness in the sediments and by local inequalities in the thickness (and hence weight) of the sediments. It is important to observe that the salt has not been thrust upward in a single intrusive movement, like an igneous invasion, but has been pushed slowly through the sediments as they were formed. Thus, the beginning of the formation of the salt domes dates far back in the Tertiary period or even pre-Tertiary time.

The Gulf Coast salt domes have great economic importance because of oil and gas that is found in the upturned Tertiary strata around the salt, and in the cap rock above the salt. Salt and sulphur are also produced from them.

The Caribbean Region

Tertiary formations occur throughout much of Cuba, Porto Rico, Haiti, Jamaica, Santo Domingo, and some lesser islands of the West Indies; also on the mainland in Panama, Nicaragua, and the Yucatan peninsula. Excepting Middle Eocene in Jamaica and Haiti, the oldest Tertiary in this region is Upper Eocene which occurs on all of the larger islands except Porto Rico. The Oligocene is extensive but relatively thin. Highly fossiliferous Miocene marine strata occur in Jamaica, and beds of similar age are found in Santo Domingo and Porto Rico. The presence and the fossil content of these Tertiary formations are not merely significant as to geological changes in the Caribbean region but bear on connections of the Atlantic and Pacific, by means of which intermigration of shallow-water marine organisms living normally on the east and west coasts, respectively, was permitted at certain times and through absence of a direct connection was prevented at other times.

Pacific Border Region

Marine Tertiary formations are distributed along the Pacific Border of North America from Lower California to Alaska, and, as in the Atlantic and Gulf Plains, nonmarine deposits are associated with the marine. Unlike the Tertiary in the east, however, that of the Pacific region occurs only in disconnected areas, which are mostly less than 100 miles across. The largest single area of Tertiary sedimentation is a troughlike basin about 450 miles long, of which the present Great Valley of California is a remnant. The western Tertiary does not make a continuous broad lowland plain, but instead it forms mountains, hills, and valleys. The beds are commonly folded steeply and faulted. The total thickness of the Pacific Tertiary (more than 40,000 feet) greatly exceeds that known anywhere in the Atlantic or Gulf region. A main reason for the smaller size and the scattered arrangement of the Tertiary outcrops is evidently due to the complex structure—to the fact that in many places only the edges of tilted beds appear at the surface.

Characteristic of the Pacific Border Tertiary is the dissimilarity in thickness and completeness of the stratigraphic sequence in closely adjacent areas. That is to say, a section of Tertiary strata in one place may have a total thickness of less than a thousand feet and may alto-

gether lack deposits of certain epochs and parts of other epochs; but only a few miles distant (in general, on the other side of a prominent fault line) the Tertiary section may be many thousands of feet thick and may show several formations that are absent in the first locality. This means great irregularity, in both kind and amount of sedimentation. Erosion of some areas took place while sedimentation proceeded in others near-by. Some blocks of the earth crust tended mainly to be pushed

FIG. 319.—Air photograph of folded and faulted Tertiary rocks in Coachella Valley southeast of Indio Hills, southern California. The fault, seen in the upper part of the view, is the San Andreas fault, which is traced some hundreds of miles southeastward from San Francisco. (*From International Geol. Congress Guidebook* 15. *By permission Spence Airplane Company.*)

upward and they supplied much sediment; other blocks tended generally to sink and they received much sediment. The sedimentary basins are mainly fault troughs. These conditions indicate that crustal adjustments and readjustments took place at frequent intervals during the time of formation of the West Coast Tertiary. There is evidence that the movements were mainly vertical, or perhaps with some horizontal components parallel to the fault planes. Indications of strong compression, such as close folding and much thrust-faulting, are not seen generally, even though the strata are very commonly tilted steeply and though overturned folds occur locally. Geologic formation names are

mostly applicable only in a single district and the number of named stratigraphic units is very large.

A condition related to those just described is the not infrequent occurrence of angular unconformities. These unconformities are local, rather than regional; and places where beds of the entire Tertiary section lie parallel are much more numerous than those in which they are discordant. Nevertheless, strata of Miocene or Pliocene age are found

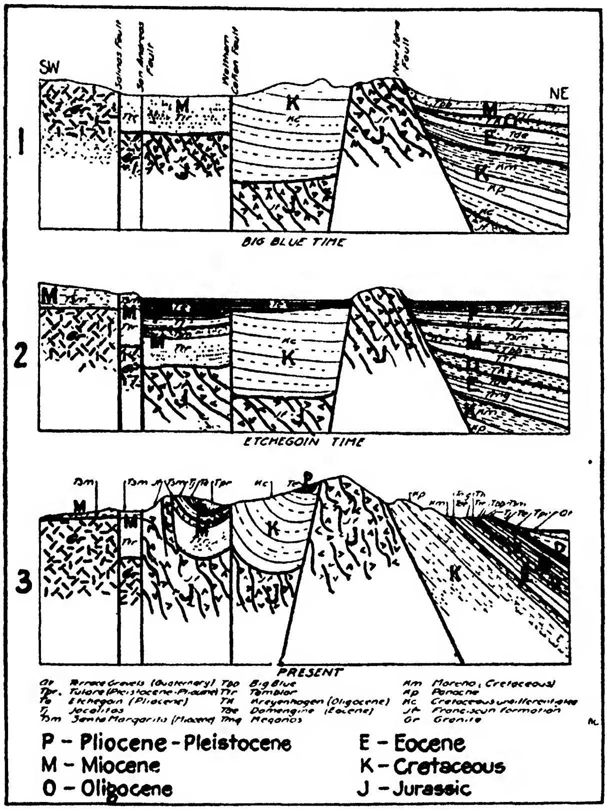

FIG. 320.—Diagrammatic sections showing fault-trough sedimentation in part of the San Andreas-New Idrea fault zone: (1) represents conditions in middle Miocene time, (2) middle Pliocene time, (3) present time, which follows folding. (*B. L. Clark.*)

resting on the eroded surface of tilted older Tertiary beds, and Eocene beds lie with angular unconformity on other Eocene beds.

Eocene Formations.—A widespread unconformity marks the base of the Eocene series. Locally, in Washington, Oregon, and part of California, this break is angular in character, but more commonly the stratification of the Eocene beds is parallel to that of the Upper Cretaceous. The Eocene deposits are chiefly marine and consist mostly of greenish gray, fine and coarse sandstone and shale. Conglomerate

occurs at the base in places and diatomaceous shale forms the upper part of the Eocene in the southern portion of the Great Valley of California. Coal beds and brackish-water deposits are found in western Oregon and Washington, overlying marine beds. The maximum thickness of the Eocene is 12,000 feet in western Oregon and 9,000 feet in southern California.

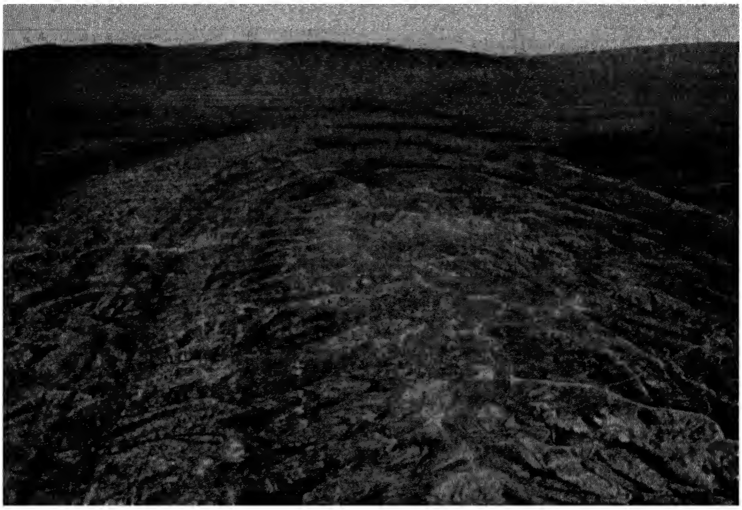

FIG. 321.—Air photograph of an anticline in Tertiary beds, Kettleman Hills, southern California. Tertiary rocks penetrated by wells drilled on this anticline have been found to contain great quantities of oil and gas. (*Courtesy R. D. Reed, The Texas Company.*)

On the basis of the fossil faunas and unconformities, the California Eocene is divided into four main parts: in upward order, Martinez, Meganos, Domengine, and Tejon. The Martinez is correlated with the

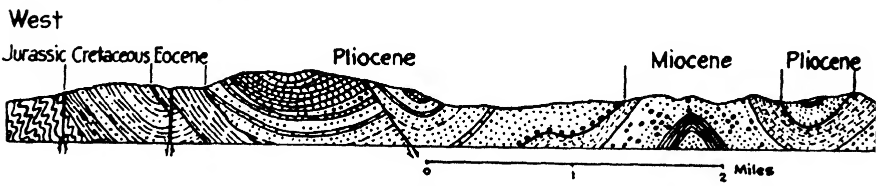

FIG. 322A.—Geologic section of folded Mesozoic and Tertiary beds in the vicinity of San Francisco Bay, California. The section extends eastward from Berkeley. (*San Francisco folio, U. S. Geol. Survey.*)

Midway group of the Gulf Coast area, the Meganos with the Wilcox, the Domengine with lower Claiborne, and the Tejon with upper Claiborne. In places the uppermost Eocene overlaps all of the lower divisions and is found resting directly on Cretaceous rocks, or even on granite. The Coast Range of Oregon contains a large thickness of Eocene rocks which include marine sandstone and shale containing much material of igneous origin derived from contemporaneous, and possibly earlier,

lava flows and tuff beds. At the top are brackish-water deposits and coal beds. Most of the Eocene rocks of the Coast Ranges are marine, and the greater part (Cowlitz) is correlated with the Tejon. The Puget Sound region of northwestern Washington contains several thousand feet of sandy beds (Puget group) that are brackish- and fresh-water in origin. The upper part of these deposits may belong to the Oligocene series. Coal beds are numerous and remains of land plants are abundant. Igneous rocks, sands, and conglomerate on the Olympic Peninsula are associated with marine fossils indicating Eocene age.

Oligocene Formations.—Deposits of Oligocene age are found in several parts of the Pacific Coast region but are best developed in Washington, where three distinct faunal horizons are recognized. The lower and middle of these faunas are warm temperate or subtropical, and it is especially interesting to note their occurrence as far north as southern Alaska. The upper fauna indicates slightly cooler conditions. Oligocene marine (San Lorenzo) and nonmarine deposits (Sespe, in part) are well distributed in California. Beds called Sespe, which are about 6,000 feet thick northwest of Los Angeles, have been recently found to include some Eocene and probably a considerable thickness of lower Miocene. The continental Oligocene consists of conglomerates, sandstones, and shales of varied colors but includes especially red beds.

Miocene Formations.—Marine formations of Miocene age are widely distributed along the Pacific Border, attaining a maximum thickness of about 12,000 feet in part of southern California. A disconformity occurs in many places at the base. Some exposures show Miocene resting directly on Eocene, indicating nondeposition or erosion of Oligocene deposits, and some show the Miocene on pre-Tertiary rocks. These relations indicate the occurrence of significant geographic changes which introduced Miocene time.

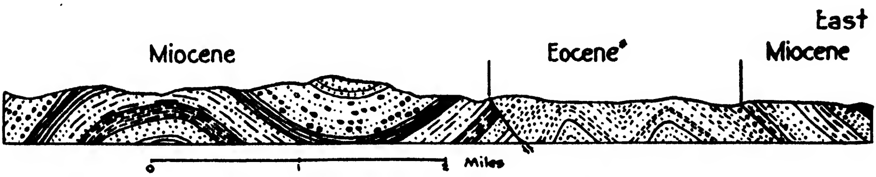

FIG. 322B.—Continuation of 322A. Note unconformities at the base of the Cretaceous, Eocene, and Pliocene. Miocene beds are absent in the west part of the section.

Two chief divisions of the Pacific Coast Miocene are generally distinguished, and these in turn are subdivided on lithologic and faunal grounds. The lower of the two main groups (called Monterey)[1] consists

[1] A great deal of confusion appears to exist in some of the Miocene correlations of California, as a result of too much reliance on lithologic comparisons. For example, recent paleontologic work indicates that the *type* Monterey is upper Miocene, although this name has been applied to the lower part of the Miocene series.

mainly of shale in which the siliceous skeletons of diatoms are commonly very abundant. These microscopic plants are considered to be a probable source of much of the California petroleum. Foraminifera and many kinds of molluscan shells occur also. The upper group (San Pablo) contains much sandy material, including in places thick and coarse arkosic sandstones but elsewhere sandy and clayey shale. The most extensive inundation of Miocene time took place very late in the epoch (late San Pablo), when many of the persistent land masses (positive elements) of the coastal region were submerged.

Pliocene Formations.—The Pliocene of the Pacific region includes many locally named deposits, some of which are marine and some conti-

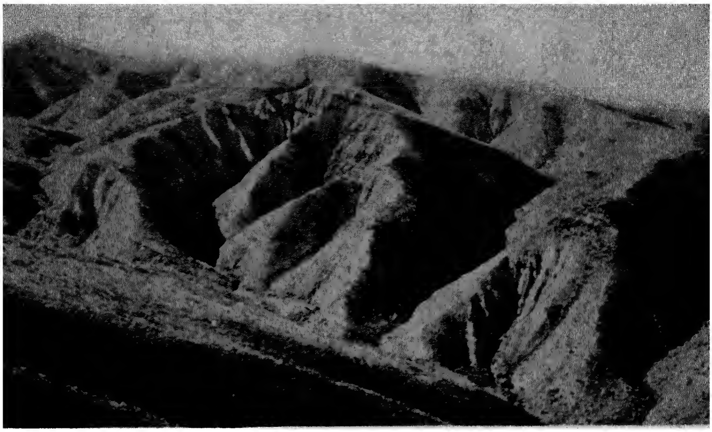

FIG. 323.—Upper Miocene beds, Fresno County, Calif. (*F. M. Anderson, U. S. Geol. Survey.*)

nental. Lithologic characters and thickness vary greatly. Some of the marine faunas are cold-temperate or boreal, presaging the glacial climates of Pleistocene times. In the Ventura region northwest of Los Angeles, more than 15,000 feet of Pliocene marine shaly and sandy beds are measured, but, in places not far distant, deposits of this age are thin or absent. Nonmarine Pliocene strata, consisting of conglomerate, sandstone, and shale, in places associated with igneous rocks (lava and tuff), are well-known in the Great Valley of California, in the Mount Diablo and Berkeley Hills regions near San Francisco, and elsewhere. The thickness of these beds locally exceeds 8,000 feet.

The Continental Interior

A large part of the Western Interior of North America is covered by Tertiary rocks of sedimentary and igneous origin (Figs. 315, 329). The aggregate area of these outcrops considerably exceeds that of all the border regions. The rocks of the Continental Interior differ from those of the Coastal Plains in that (1) none of the sediments is marine,

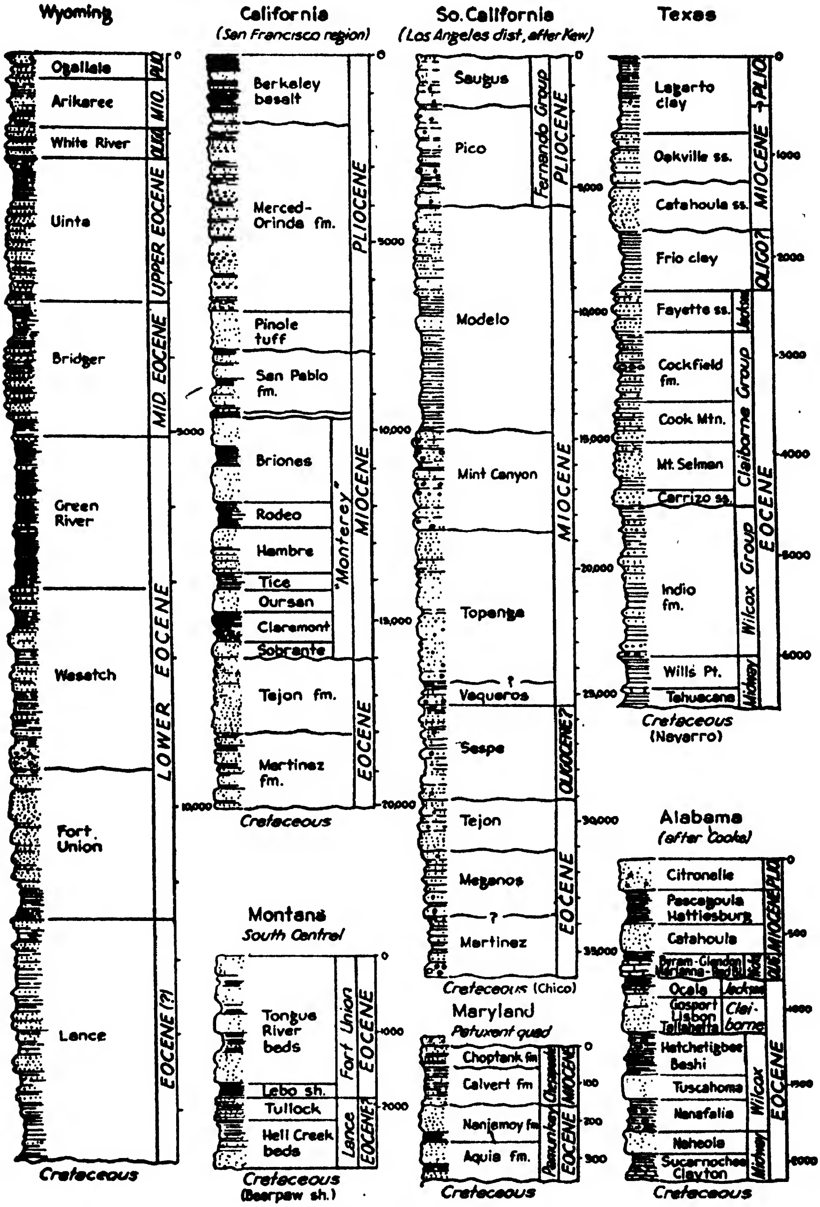

Fig. 324.—Generalized sections of the Tertiary system in selected areas.

(2) limestones and marls are almost lacking (except in the Eocene Green River formation) but sandstone and conglomerate are very common, and (3) igneous rocks, including lava, tuff, agglomerate, ash, and intrusive material, are proportionally and quantitatively very important. Because of the considerable topographic relief of many parts of the region containing these beds and because of lithologic characters of the beds, the outcrops of the Tertiary show a variety of interesting scenic features, including varicolored and fantastically carved mesas, cliffs, and badlands. Other parts of the Continental Interior Tertiary areas are featureless plains. The igneous rocks form lofty mountains and also broad plateaus and plains.

The outstanding characters of the Tertiary formations in this region are dominance of clastic materials and variation in the deposits from place to place. The chief agent of sedimentation was running water. The basins between mountain uplifts were filled by alluvial fan materials, flood-plain sediments, sheet wash, and in smaller degree lake deposits and wind-blown sand and dust. The basins were partly isolated and disconnected, but in the Wyoming and adjacent region and in the plains country east of the Rockies extensive sheets of continuous formations were made. The thickness of the continental Tertiary deposits ranges from less than 100 feet to many thousands of feet. In general, the Tertiary (mainly older Tertiary) of the western intermontane basins is very thick, but that (mainly younger Tertiary) of the plains east of the Rockies is thin.

Eocene Formations.—Formations of Eocene age are widespread. Some of the most important areas are (1) the San Juan Basin of northwestern New Mexico and southwestern Colorado, (2) the Trinidad and Denver districts east of the Rockies in Colorado, (3) the Uinta Basin in northeastern Utah and northwestern Colorado, (4) the Green River and Wind River basins in southwestern Wyoming, (5) the Bighorn Basin in northwestern Wyoming, (6) a great territory in eastern Wyoming, Montana, and the western Dakotas, and (7) another large area in Alberta. The formations in these various places are not precisely equivalent. Older Eocene is prominent in some but unimportant or lacking in others, and younger Eocene is very thick in some basins while absent in others. These conclusions are based mainly on observation of the distribution of fossil mammals. Broadly speaking, the most primitive types occur in the oldest deposits and more advanced kinds in the younger. The succession of mammalian faunas is not completely recorded in the Eocene section of any one basin but must be pieced together from studies in different areas. Because knowledge of the animal life of the epoch is fragmentary, in spite of the host of species obtained by long collecting, and because variations due to geography and environment are difficult to evaluate, it is not possible in all cases

to determine the precise relations of deposits in different districts. The problem is really a complex one. As commonly recognized, the main ages or stages within the Eocene are, in order from oldest to youngest, (1) Fort Union, (2) Wasatch, (3) Green River, (4) Bridger, and (5) Uinta.

The *Fort Union* beds consist mostly of thick irregularly cross-bedded, light-colored sandstone and dark shale. Coal beds are prominent in parts of the northern Eocene districts. Locally the natural burning of these coals has so heated and baked the adjacent shaly rocks as to

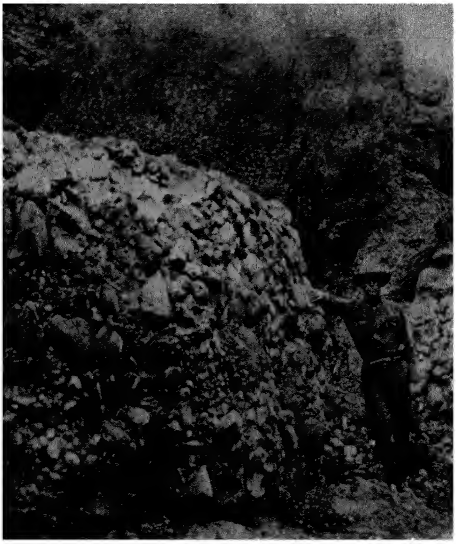

FIG. 325.—Coarse conglomerate of early Eocene (Wasatch) age, near Thistle, Utah. A great mountain-making movement, comprising part of the Laramide revolution, shortly preceded deposition of the Wasatch beds. Materials derived from the erosion of the mountains and other highlands are found in the Eocene deposits of the west. (*E. M. Spieker, U. S. Geol. Survey.*)

produce a hard reddish bricklike mass that may be traced for miles. The sandstones make prominent escarpments. The average thickness of the Fort Union beds is about 1,000 feet and the maximum more than 8,000 feet. The Fort Union (and adjacent Lance) strata are in a sense transition deposits between Cretaceous and Tertiary and are set off by some in a separate series called Paleocene.

The *Wasatch* beds include variegated clays, shales, fresh-water limestones, coals, sandstones, and conglomerates. Deposits of this age are very widely distributed and a prominent unconformity is generally present at the base. The "Pink Cliffs," at the margin of the High Plateaus of southern Utah (Fig. 237), are composed of Wasatch deposits, the coloring and local elaborate carving of which produce such unusual

scenic features as Bryce Canyon (Fig. 313). The thickness of Wasatch beds ranges up to about 7,000 feet, but it is mostly much less.

The *Green River* formation consists mainly of lake deposits that covered an area of 50,000 square miles or more in northwestern Colorado, Utah, and Wyoming. The beds are mostly thin and very evenly stratified. Shale predominates, and, because of the large organic content of many layers that yield oil on distillation, the beds are called oil shale. Sandstone and limestone also occur. The thickness of the Green River formation ranges up to 2,000 feet.

The *Bridger* and *Uinta* beds are shaly and sandy deposits that are mainly of fluviatile origin. They are typically developed in southwestern Wyoming and northeastern Utah, where the total thickness is approxi-

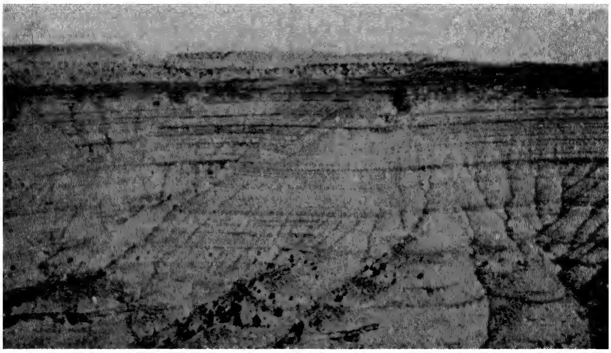

FIG. 326.—Evenly bedded deposits of an Eocene lake. Green River shale in northeastern Utah near Watson. This formation, which extends over much of northwestern Colorado and into southwestern Wyoming, contains rich oil shale beds. (*D. E. Winchester, U. S. Geol. Survey.*)

mately 3,000 feet. A number of fossil zones are recognized, each of which is distinguished by a certain group of mammals.

Oligocene Formations.—Continental deposits of Oligocene age are known in the western United States chiefly from two regions, the northern Great Plains and north central Oregon. The Big Badlands southeast of the Black Hills in South Dakota afford the best exposures of the plains Oligocene, which is called White River. The sands and clay, containing numerous remains of mammals, rest unconformably on eroded Cretaceous rocks. The total thickness of the Oligocene is about 800 feet. The Oregon locality (John Day Basin) shows some hundreds of feet of shale, ash, tuff, and lava beds, that are well-known because of finely preserved leaves and mammal fossils found in them.

Miocene and Pliocene Formations.—Later Tertiary deposits are most extensive in the Great Plains country reaching from South Dakota to Texas. Clay, sand, and gravel deposited by streams that flowed eastward from the Rockies contain in various places bones of mammals which show that parts of the beds are Miocene and part Pliocene in age.

The thickness is not great, being mostly less than 200 feet. Because of the pervious character of these Tertiary beds and the relatively impervious nature of underlying Cretaceous strata, the former are an important source of underground water.

A local but unusually interesting Miocene deposit occurs in the Rocky Mountains west of Colorado Springs. This is the fine, evenly bedded

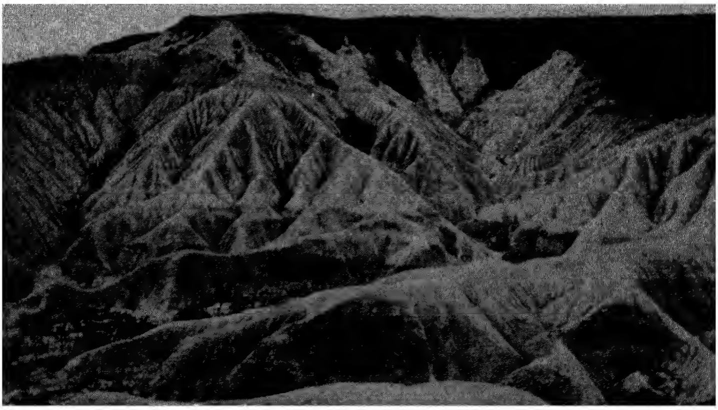

FIG. 327.—Oligocene beds (Brule) in the Badlands of South Dakota and northwestern Nebraska. Near Chadron, Nebr. (*N. H. Darton, U. S. Geol. Survey.*)

silt and volcanic ash of an ancient lake in which abundant leaves, insects, and other organisms are preserved (Florissant beds).

Igneous Rocks.—The igneous rocks of Tertiary age are very important in western North America, for they cover more than 300,000 square miles and in places are several thousands of feet thick. Eruptive rocks consisting of lavas, tuff, and ash are predominant but there are also

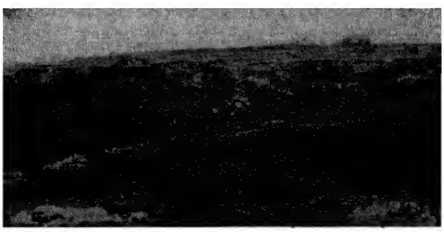

FIG. 328.—Outcrop of Pliocene beds (Ogallala) consisting of sand cemented by calcium carbonate and clay. Ellis County, western Kansas. (*N. W. Bass, Kansas Geol. Survey.*)

many intrusive masses—dikes, sills, plugs, laccoliths, and batholiths. Rugged mountains composed of Tertiary igneous rocks occur in the San Juan region of southwestern Colorado, the Mount Taylor area in New Mexico, the San Francisco and lesser mountain groups in Arizona, the Cascades, and parts of the northern Rockies. Prominent isolated peaks of volcanic origin such as Mounts Shasta, Hood, and Rainier are

at least as ancient as the later Tertiary. Laccolithic mountains occur in Utah (Henry, La Sal, Abajo), Colorado, and other states. Plateaus and mesas capped or built entirely of lava flows are widely distributed

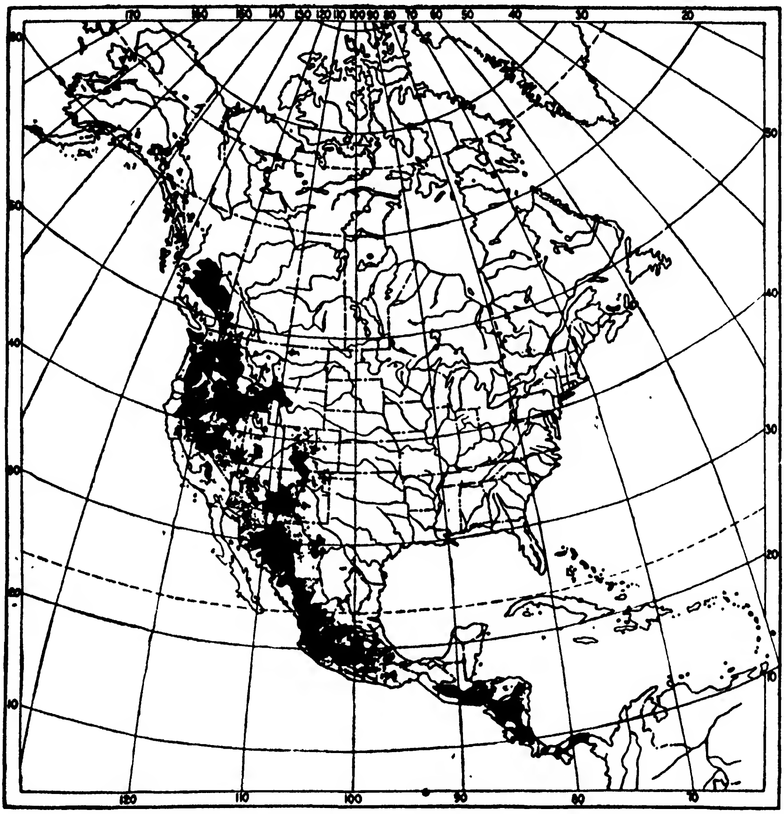

FIG. 329.—Map of North America showing areas covered by volcanic rocks of Tertiary age (black). (*V. R. D. Kirkham, in Chamberlin and Salisbury's Historical Geology, Henry Holt & Company.*)

and some are many thousands of square miles in extent. The largest of the plateau areas is in the Columbia and Snake River region of Washing-

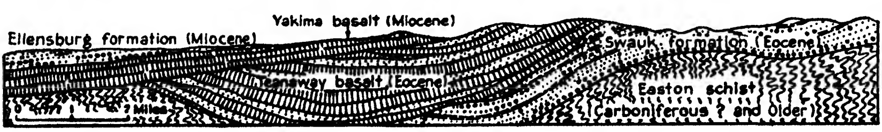

FIG. 330.—Geologic section of Tertiary formations in the Cascade Mountains north of Ellensburg, east central Washington (Mount Stuart quadrangle). Basalt lava flows totaling thousands of feet in thickness are an important feature of the Eocene and Miocene rocks in this district. (*U. S. Geol. Survey.*)

ton, Oregon, Nevada, and Idaho. There are innumerable separate lava flows, one above another, the average thickness being about 75 feet. Occurrence of stream-laid sand and gravel and in places thick soil with

standing stumps of large trees between the lava sheets prove that much time elapsed between some of the eruptions. A natural section of volcanic beds in Yellowstone Park shows 15 successive forest beds, some with trunks up to 10 feet in diameter. The aggregate thickness of the eruptions in many places is more than 5,000 feet.

Because of the prevalence of volcanic activity in the western part of the continent during Tertiary time, much of the sedimentary deposits in this region consists of igneous materials.

TERTIARY FORMATIONS OF OTHER CONTINENTS

Eurasia

The Tertiary formations of Europe and Asia are essentially a unit and may be considered conveniently together. The outcrops are very extensive, especially in the Mediterranean region and its former eastward continuation that comprises part of the sea called Tethys. This is a region of very thick Tertiary deposits and it is characterized by complex folding and faulting which are associated with formation of one of the greatest mountain chains of the earth. The sediments are largely marine but there are also thick continental formations.

Eocene.—Rocks of Eocene age occur throughout most of southern Europe and are found in southeastern England, northern France, Belgium, Holland, and Germany. In the Mediterranean region the chief deposit is a widespread marine limestone that in places attains a thickness measured in thousands of feet. It is mainly composed of the large coin-shaped Foraminifera called *Nummulites* and is hence known as the nummulitic limestone. This early Tertiary formation furnished the stone, laboriously quarried and shaped in large blocks, that went to the building of the pyramids by ancient Egyptians. The nummulitic limestone occurs in Asia Minor, Turkestan, Persia, and the belt occupied by the Himalayas which in Eocene time was below sea level.

The Paris Basin contains Eocene beds that have been much studied and constitute the type section for the northern hemisphere. Marine limestones and calcareous sands of this basin are especially famous for the abundance, variety, and perfection of preservation of their invertebrate fossils. There are also thick gypsum deposits, in which skeletons of mammals are found, and fresh-water beds containing numerous plants. The vertebrate remains are important partly because they were the materials used by the great naturalist Cuvier, in laying the foundations of comparative anatomy and vertebrate paleontology.

Oligocene.—The distribution and general nature of Oligocene formations in Europe are not very unlike those of the Eocene. The southern Oligocene is chiefly marine and in places very thick. The northern deposits occur in local basins, are more variable in lithologic character, and include normal marine, brackish, fresh-water, and highly saline sediments. There are beds of brown coal (lignite) in northern Germany, and gypsum, salt, and potash salts in Alsace and Spain. Considerable volcanic activity is evidenced by lava flows in central Europe, the northwestern part of the British Isles, and Iceland. Southeastern Europe and the Caucasus region of western Asia contain very thick, relatively unfossiliferous deposits (Flysch) consisting of water-laid gravel, sand, and clay.

Folding of Oligocene and older strata in the area now occupied by the Alps, Apennines, Pyrenees, Carpathians, Caucasus, and Himalayas occurred toward the close of the Oligocene epoch. The mountains that were formed by this extensive crustal movement began to be eroded and supplied much coarse sediment to neighboring areas in Miocene time.

Miocene.—The marine formations of Miocene age are mostly confined to the southern part of Europe and a belt that extends eastward across west central Asia. Very fossiliferous strata are found in southern France, Italy, and the Vienna Basin of Austria. Adjacent to the Carpathians in Rumania there are lagoonal deposits with much salt. Post-Miocene compression of the salt-bearing beds has produced salt domes of complex structure. Salt is also found in the Miocene of northern India.

Most of northern Europe is lacking in Miocene deposits. Marine strata of this age are present in part of Belgium and the Netherlands. On the north flank of the Alps the Miocene includes coarse conglomerate, to about 6,000 feet thick, that was derived from erosion of mountainous areas then existing to the south.

Renewal of mountain-building near the close of Miocene time caused deformation of Miocene beds and complicated the structures formed by folding and faulting in earlier Tertiary time. This movement affected the sites of the Alps and other chains from the Pyrenees eastward to the Himalayas.

Pliocene.—The outlines of the Eurasiatic continent in Pliocene time were almost those of modern times. Small areas of marine deposits of this age in southeastern England, Belgium, Holland, and northwestern Germany indicate a slight invasion of the North Sea. Italy and southern France contain the chief marine Pliocene beds of the Mediterranean region. Volcanic materials are found, especially in Italy and Sicily which still contain active volcanoes like Vesuvius and Etna. Southeastern Europe and western Asia are covered by fairly extensive continental deposits of Pliocene age.

Another important crustal disturbance is recorded at the close of Pliocene time in the great mountain chains of southern Europe and central Asia. The net result of the various deformations that have affected this belt is witnessed in the extremely complex, highly contorted folding of beds, in the numerous low-angle thrust faults along which great masses of rock have been carried irresistibly for many miles, and in the topographic elevation of the mountain chains. Many of the thrust-fault planes have themselves been folded and faulted. Pliocene marine strata have been lifted at least 3,000 feet above the sea in the Apennines, and the Eocene nummulitic limestone occurs at an elevation of 10,000 feet in the Alps and nearly 20,000 feet in the Himalayas. The latter mountains are the loftiest in the world, the dominant peak Mount Everest rising to 29,140 feet.

Africa

The Tertiary formations of Africa occur chiefly in the northern part of the continent, where advances of the Mediterranean, especially in Eocene and Miocene, are recorded by marine limestone and other sediments. This continent has been relatively stable and emergent during post-Paleozoic time.

Australia

Only minor portions of Australia are covered by Tertiary deposits but in places there are extensive lava flows and thick beds of volcanic tuff of this age. Adjacent islands of the East Indies contain thick Tertiary formations, partly marine and partly nonmarine. The beds are strongly folded and there is evidence of considerable vulcanism. These features are also observed in New Zealand.

South America

Patagonia, in the southern part of South America, has the largest area of Tertiary beds on this continent. However, there are thick deposits of this age along the Pacific and the Caribbean. The Andean chain was strongly elevated at or near the close of Tertiary time.

PHYSICAL HISTORY OF TERTIARY TIME

The main features in the physical history of Tertiary time, as recorded by characters of the Tertiary formations that have been described and also in part by physiographic characters of the continents, are (1) successive marine invasions of the continental borders, (2) extensive sedimentation by streams and in smaller degree by lakes in parts of the continental interiors, (3) erosion of the lands, forming peneplains in many places, (4) widespread mountain-building, and (5) vulcanism. All of these features make contribution toward conditions of the present and there is a progressive approach during Tertiary time toward the modern world. Let us review the epochs of the period briefly in chronologic order, following chiefly the history of North America.

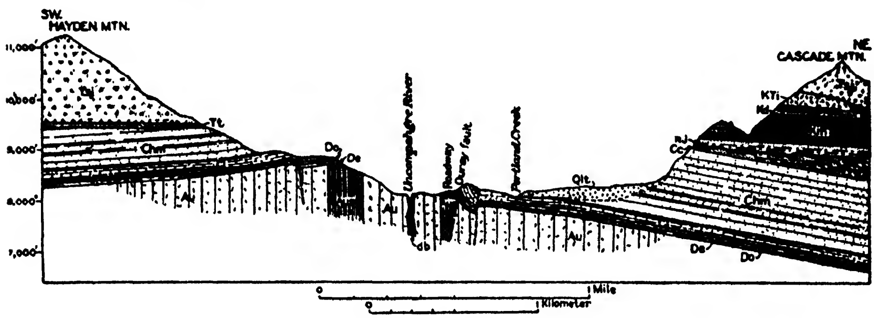

FIG. 331.—Geologic section in the San Juan Mountains of southwestern Colorado showing Tertiary volcanic rocks (San Juan tuff, *Tsj*) and basal conglomerate (Telluride conglomerate, *Tt*), resting unconformably on Pennsylvanian (Hermosa formation, *Chm*) and Permian (Cutler formation, *Cc*) beds. In this locality Devonian (*De*) rests unconformably on strongly folded Proterozoic quartzite and slate (*Au*, *Aus*). (*U. S. Geol. Survey.*)

Eocene Epoch.—At the beginning of Eocene time the continent was probably as large as or larger than now, for an unconformity occurs almost everywhere at the base of the marine Tertiary. The sea soon advanced nearly to the inner margin of the Atlantic and Gulf Coastal Plains, reaching northward in the Mississippi embayment to the position of the mouth of the Ohio River; on the Pacific Coast the sea invaded the Great Valley of California, the site of the present Coast Range from California to Washington, and locally territory farther north. Temporary recessions of the sea are marked by unconformities and in places by continental deposits. The epoch was long, there was considerable oscillation of the strand line, and thick deposits were formed. The extensive sea in which great thicknesses of nummulitic limestone were deposited is most noteworthy in the Eocene of the Old World.

Basins of the Cordilleran region became the site of much sedimentation by streams, lakes, and possibly winds. Coal beds were made in broad marshes. The mountains that were formed near the close of

Mesozoic time furnished an abundance of gravel, sand, and silt which was spread out to make the locally variable continental deposits that are hundreds to thousands of feet in thickness. Calcareous beds and dark-colored oil shale were formed in lakes. The formations of this epoch are thicker and more extensive than any other Tertiary series of the Western Interior region. There was much volcanic activity in Utah and elsewhere.

Oligocene Epoch.—The sea of Oligocene time covered parts of the present land of the southern Atlantic and Gulf Coast Plains but did not advance nearly so far inland as in the preceding epoch. The Florida Peninsula was blanketed by Oligocene marine sediments. On the Pacific Border the sea of Oligocene time was apparently more restricted than that of the Eocene, and in places there are thick nonmarine deposits adjacent to the present coast.

The interior of North America was undergoing erosion in most places during the Oligocene epoch. The chief and almost the only place where deposits of this age are well developed is in the Black Hills area, where stream beds carrying abundant bones of mammals occur. Probably the beginning of some of the major geographic features of the west, such as establishment of the general course of the Colorado River drainage and topographic differentiation of certain plateau and mountain areas, belongs here.

The beginning of the great Eurasiatic mountain belt that includes the Alps and Himalayas is dated at about the close of Oligocene time.

Miocene Epoch.—The Miocene sea advanced to the inner margin of the northern Atlantic Coastal Plain but farther south and in the Gulf it did not extend so far, in general, as the Oligocene. Part of Florida was apparently land. In the Pacific region the deposition of thick shale, in part with exceedingly abundant diatoms, is a feature of the marine record.

Nonmarine deposition in Miocene time was extensive in the northern Great Plains but the beds are not very thick. This was a time of stupendous igneous activity in the northwestern part of the United States. The volume of extruded lava measures thousands of cubic miles, and in addition there are great quantities of ash, cinders, and volcanic tuff.

Erosion of the land was proceeding constantly but at varying rates in areas not subject to sedimentation. This is true of each of the Tertiary epochs and it is generally not possible to determine the amount of erosion accomplished in a given epoch or to fix the exact age of a peneplain when fossil-bearing sedimentary deposits associated with the erosion surface are lacking. The development of the Harrisburg peneplain in the Appalachian region may belong to Miocene time or, according to the view of some physiographers erosion of this epoch, may be represented in the higher, older Schooley peneplain. The Rocky Mountain

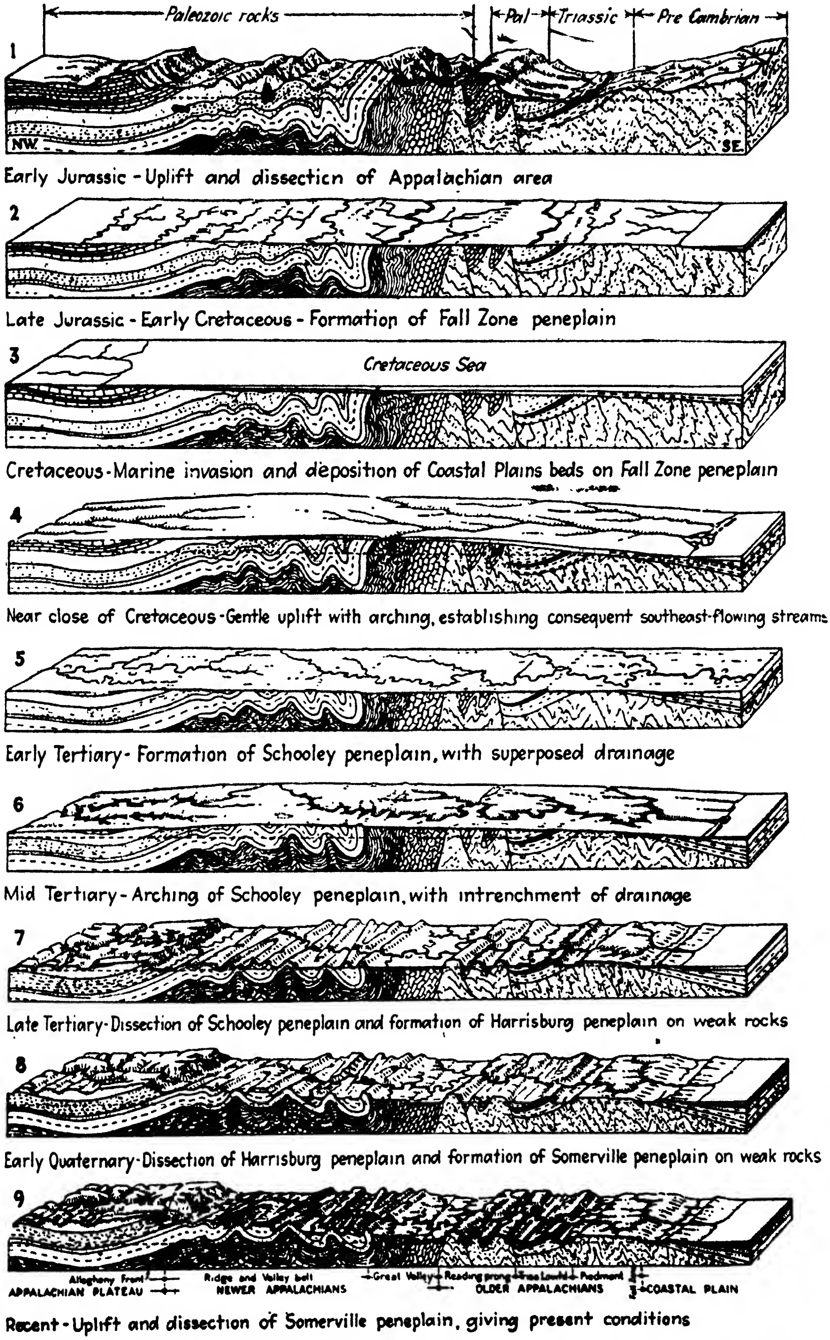

Fig. 332.—Diagrams representing stages in the physiographic history of the Appalachian region. (Geologic age assignments tentative, by R. C. Moore.) (*D. W. Johnson, Columbia University Press.*)

region and much of the plateau country farther west was peneplaned during Tertiary time, as was the Sierra Nevada Range. The most widely recognized and well-marked peneplain of these western areas is regarded as having been made by the close of Miocene time. Subsequent uplifts have caused the obliteration of large parts of the peneplains.

Structural disturbances affected parts of North America at about this time, possibly near the close of the Miocene. A series of great normal faults trending north-south intersect the Colorado Plateau province in Arizona and Utah, the vertical displacement on some amounting to more than 10,000 feet. There were similar disturbances in some other places. Mountain-building movements in the Alpine-Hamalaya chain have been mentioned.

Pliocene Epoch.—The last part of the Tertiary period is marked by a further approach to the general geographic conditions of today. The outlines of the continents accorded fairly closely with those existing now but various mountain ranges were apparently less elevated during Pliocene time than after the disturbance at the end of this epoch. Marine sedimentation is best recorded in the Gulf and California regions of North America and the Mediterranean region of Europe. Continental deposits were made on the plains and some intermontane basins of the western United States and in southeastern Europe and adjacent parts of Asia.

Close of the Period.—The general uplift accompanied by rejuvenation of old mountains that occurred at the close of Tertiary time in North America has been called the *Cascadian revolution*. The area of the Cascade Mountains in the Pacific northwest had been intensely folded at the close of the Jurassic and subsequently peneplaned. The post-Pliocene uplift of this region amounts to some thousands of feet and the present mountains have been formed by carving of innumerable deep canyons. Similarly, the Sierra Nevada Range which was peneplaned in the Tertiary period was strongly elevated, the mountain block being pushed upward along a major fault and fold at the east margin of the range and tilted westward. Mount Whitney (14,500 feet), highest peak in the United States, excepting Alaska, is a point near the east front of the Sierra Nevadas. Much faulting appears to have occurred near the close of Tertiary time in the Great Basin region where numerous north-south-trending mountain ranges are found. There was folding of Pliocene beds in the Coast Range of California and uplift of Alaskan mountain chains.

The Rocky Mountains and the Colorado Plateau province appear to have been elevated at the close of the Tertiary. There are clearly marked evidences of peneplanation in this territory, the erosion having been accomplished during Tertiary time. Subsequent uplift has caused rejuvenation of streams and resulted in the carving of deep canyons,

greatest of which in width and length is the Grand Canyon of the Colorado River in northern Arizona.

The Mississippi Valley region has been a low-lying land area since the end of Paleozoic time. Throughout the very long Mesozoic and Cenozoic eras there has been neither very much erosion nor deposition here. A general elevation of a few hundred feet that occurred near the close of the Tertiary, however, has caused deepening of valleys and accentuation of local relief in most of this territory. There are many physiographic evidences of this uplift and of its relatively recent date.

The Appalachian Mountains and the eastern seaboard may be included in the list of areas affected by uplift at the close of the Tertiary period. Peneplains of Pliocene and older date have been partially dissected by post-Tertiary erosion. The existence of submerged channels of streams like the Hudson and Susquehanna, extending out to the edge

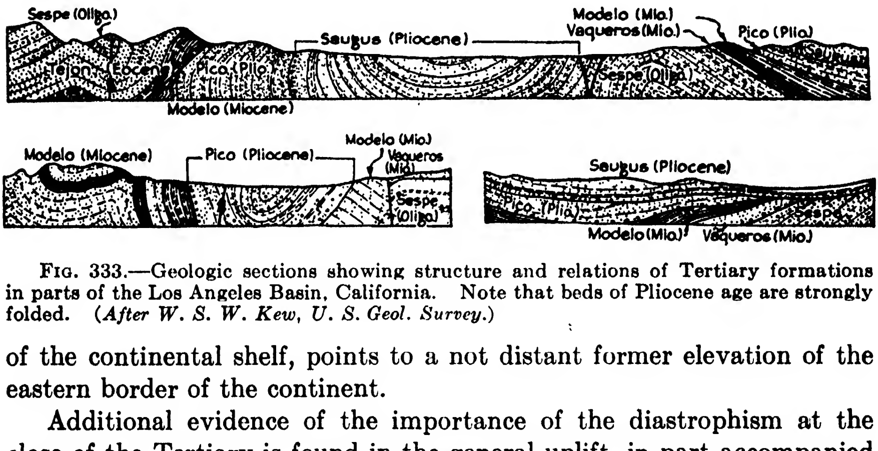

FIG. 333.—Geologic sections showing structure and relations of Tertiary formations in parts of the Los Angeles Basin, California. Note that beds of Pliocene age are strongly folded. (*After W. S. W. Kew, U. S. Geol. Survey.*)

of the continental shelf, points to a not distant former elevation of the eastern border of the continent.

Additional evidence of the importance of the diastrophism at the close of the Tertiary is found in the general uplift, in part accompanied by folding and faulting, of the great Alps-Himalayan mountain chain of Eurasia. Also, the occurrence of continental glaciation during Quaternary time was undoubtedly influenced, if not largely produced, by changes in topographic and climatic conditions that belong to this time of crustal movement.

Climate.—The character and distribution of plants in the Tertiary continental deposits afford chief basis for inferences concerning climate in the period. In the Eocene, especially, there is evidence of mild, perhaps subtropical, temperatures in the Western Interior region as far north as Canada, for palm leaves 3 feet wide and leaves of the fig, magnolia, and other warmth-loving plants (if we may judge from modern species) are found in this region. The climate was also generally humid. The Gulf Coast region has yielded remains of the breadfruit tree and other plants that are now confined to the tropics. Even the far north enjoyed a congenial, if not a distinctly warm, climate. A rich Upper

Eocene flora from the west coast of Greenland contains species of oaks, elms, maples, walnuts, persimmons, magnolias, plums, beeches, and many other temperate types of plants. As noted recently by Berry, however, the high-latitude floras of Early Tertiary time are not at all indicative of subtropical conditions, as has been suggested by some students.

Oligocene climates were apparently not very unlike those of the preceding epoch, although there is a suggestion of somewhat cooler and in some regions drier conditions. Fossil palms occur in northern Germany. The abundance of mammals with teeth adapted for grazing on tough plains grasses, rather than for browsing on leaves of trees and shrubs, may be regarded as a sign of dwindling forests and expanding prairies.

Miocene time seems to have been distinctly cooler on the average than Oligocene or Eocene. Abundant plants are known from a few localities but there is insufficient knowledge of the flora of North America or the world as a whole to draw very definite conclusions. There were probably distinct climatic zones such as exist today, belts of cooler and warmer temperature, and areas of drier and more humid, moist conditions. The country near Lake Florissant in Colorado contained a larger and more varied assemblage of plants in Miocene time than exists in this region now, and there are several kinds that are represented today by species living only in warm temperate portions of the Old World. The sequoias, now known by the redwoods and "big trees" of the North American Pacific Coast, were common in Colorado as well as in Greenland and Europe.

The Pliocene epoch appears to have been distinguished by increasing coolness and dryness and there was undoubtedly considerable variation in conditions in different regions. Except locally, the land floras are poorly preserved. In parts of the shallow seas of the continental shelf, cold-water invertebrates replace the types adapted to warmer conditions. This has little bearing, however, on climate of the lands, since change in the character of marine faunas may be due mainly to shifting or extension of oceanic currents without important influence on temperature of adjacent lands.

ECONOMIC PRODUCTS

The Tertiary formations yield a variety of materials useful to man.

About one-half of the world's *oil* supply is obtained from these comparatively young rocks, the chief producing territories being found in California, the Gulf Coast region of North and South America, Peru, Rumania, southeastern Russia, and the Dutch East Indies. The oil-bearing sediments consist mostly of sands that are only partly consolidated. The wells range in depth from a few hundred feet to more than 9,500 feet (in California). The structure of the beds in several of the fields is distinguished by steep folding and faulting. In addition to the oil obtained from wells,

the Tertiary oil-shale deposits of northwestern Colorado and adjacent parts of Wyoming and Utah are a tremendous potential source of supply, but the oil is obtainable only by mining and heating the shale.

Extensive *coal* beds occur in the Tertiary of the Western Interior of North America, the Gulf Coast region, and in parts of the Old World. There are many coal beds, some of unusual thickness, in the Tertiary formations of western Washington. The

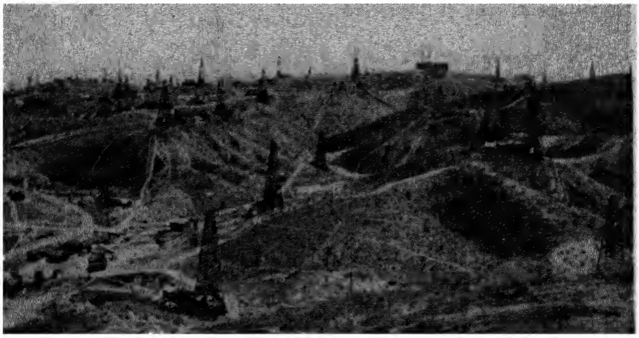

FIG. 334.—The Midway oil field, typical of many fields in the Tertiary area of the Pacific Coast. (*G. S. Rogers, U. S. Geol. Survey.*)

most important commercial development of Tertiary coals is in New Mexico, Colorado, Wyoming, and Montana and in northern Germany.

Other valuable materials of sedimentary origin obtained from the Tertiary formations are *lime phosphate* (Florida) used as fertilizer, *building stone, clays* including some very fine pottery clays, *diatomaceous earth, hydraulic lime,* and *natural gas.*

Igneous intrusions and associated ore-bearing veins of Tertiary age are the source of very important deposits of some of the metals. Chief among these are *gold* deposits,

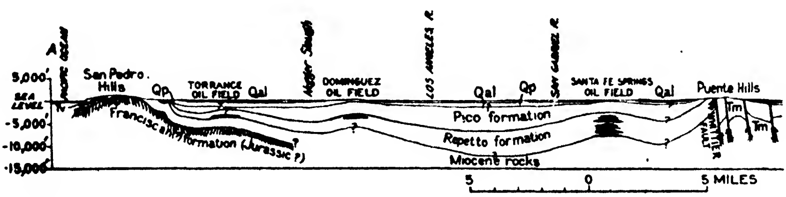

FIG. 335.—Geologic section of the Los Angeles Basin showing structural position of oil fields. (*U. S. Geol. Survey.*)

such as those of the famous Cripple Creek district, Colorado, Tonopah, Nev., and veins of the Sierras of California that supplied large quantities of placer gold; great quantities of *copper,* as at Butte, Mont., and Bingham, Utah; and in various places *silver, lead, zinc, quicksilver,* and other metals. The igneous activity and accompanying ore formation of Tertiary time are thus of much economic importance.

SUMMARY

The Tertiary system consists mainly of poorly consolidated marine and nonmarine sedimentary rocks that are separated from Mesozoic strata in most places by a disconformity or unconformity. There are also enormous quantities of Tertiary igneous rocks.

Four series are commonly differentiated: in upward order, Eocene, Oligocene, Miocene, and Pliocene. These names were intended to denote the general proportion of living to extinct species of marine organisms, in which there is a gradual approach to modern conditions.

The Atlantic and Gulf Coastal Plains of North America contain outcrops of Tertiary marine and nonmarine beds extending from New Jersey into Mexico. The surface of Florida is entirely composed of Tertiary or younger rocks, and in the Mississippi embayment outcrops of Tertiary formations extend northward slightly beyond the mouth of the Ohio River. The Tertiary formations dip gently seaward, some of the harder beds forming cuestas. Commonly there is an increase in thickness of formations or series in a seaward direction from the outcrops, and in some cases well borings show a transition from nonmarine deposits at and near the outcrops to marine deposits between the outcrops and the present seacoast. The thickness of the Tertiary strata of the Atlantic Coastal Plain is less than 1,500 feet in most places, but in the Mississippi embayment region of the Gulf Coastal Plain the total thickness may exceed 30,000 feet.

The occurrence of numerous salt domes is an interesting feature of the Tertiary area in the Louisiana and Texas portion of the Gulf Coastal Plain. Salt masses of cylindrical form, a mile or more in diameter, are thrust upward many thousands of feet through the Tertiary strata, bowing the edges of the strata upward. Oil and gas are found in many cases on the flanks and above the salt cores.

Tertiary sedimentary rocks with a maximum thickness of more than 40,000 feet occur near the Pacific Coast. The beds are much folded and faulted. They form mountains, hills, and valleys. There is much local variation in the thickness and in the stratigraphic succession of Tertiary deposits. The controlling factor in the history of Tertiary sedimentation in this region appears to have been the existence of fault-bounded crustal blocks, some of which tended to sink and others to rise periodically. The depressed or negative earth segments received a thick load of sediments. Compressive forces have tilted and folded the sedimentary strata.

The Continental Interior contains widespread areas of Tertiary nonmarine sedimentary deposits and also a very great quantity of volcanic rocks. The Rocky Mountains region, including especially areas in New Mexico, Colorado, Utah, Wyoming, and Montana, shows the greatest development of Eocene beds, which in some districts are several thousands of feet in thickness. A remarkable record of the Early Tertiary mammal faunas is obtained from these rocks. Important deposits of coal and oil shale occur. Oligocene beds are comparatively thin and local, the chief area being the Badlands country of South Dakota. Miocene and Pliocene deposits are found in many places but are quantitatively of

much less importance than the Eocene formations. Late Tertiary beds are very widespread on the plains east of the Rockies, but the deposits are comparatively thin. Igneous rocks of Tertiary age include especially the great lava outpourings of the Columbia River region and volcanic rocks of the Rocky Mountain region.

Tertiary deposits are more or less important in all of the other continents. In Europe the Tertiary beds of the London, Paris, and Vienna Basins and of Italy are subjects of classic studies. The thick nummulite-bearing limestone of the Mediterranean region extends eastward far into central Asia and is now found high in the Himalaya Mountains.

CHAPTER XXVIII

THE QUATERNARY PERIOD

Quaternary time is very short compared with other geologic periods, but, because it includes the present and most recent geologic past, its history is especially interesting and important to man. The beginning of the Quaternary period dates back a mere million years or so, and therefore the record is so recently inscribed that multitudinous details can be read clearly. Not only are there many sorts of sedimentary deposits and large quantities of igneous rocks but the work of erosion

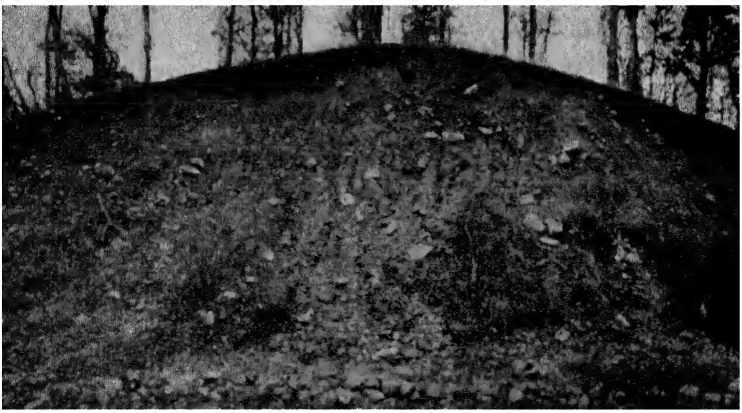

FIG. 336.—Pleistocene glacial till, Long Island. (*W. C. Alden, U. S. Geol. Survey.*)

during the period is marked by innumerable features of the present land surface. Historical geology merges here with physiography.

The outstanding feature in the history of Quaternary time is extensive continental glaciation in the Northern Hemisphere. Although ice covered only a fraction of the total land surface of the globe, effects of the glaciation were world-wide, for important changes in climate and conditions of erosion and deposition affected nonglaciated as well as glaciated territory. Changed environments influenced life on land and to some extent in the sea. World-wide changes of oceanic levels were caused by the removal of water to make the continental glaciers and by the return of water when the glaciers melted. In addition there were crustal disturbances which include broad warping of continents and local mountain-making movements.

After the rocks called Tertiary were recognized and defined, the name Quaternary came to be applied many years ago by French and German geologists to the unconsolidated surficial materials such as the alluvium of stream valleys, recent deposits in lakes and swamps, dune sand, and glacial deposits.

It was not at first understood that the widespread glacial materials of northern Europe and North America were deposits made by great continental ice sheets. These deposits were called "drift" because it was thought that they were drifted over the land surface when waters of the Noachian deluge covered the earth. Boulders of the drift were presumably carried by icebergs and deposited when the floating ice melted. When the boulder-laden bergs chanced to graze bedrock beneath the water, scratches (striae) might be made on the bedrock and boulders.

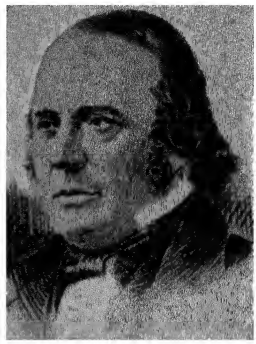

Fig. 337.—Louis Agassiz (1807–1873).

When Agassiz, in 1837, put forward the thesis not only that glaciers of the Alps had formerly spread far out on the plains at the foot of the mountains but that all of northern Europe had been buried by a huge glacier in comparatively recent geologic time, the scientific world was incredulous. But so completely and irrefutably has the correctness of Agassiz's deductions been established, both in Europe and in North America, that there can be no slightest doubt as to the actuality of extensive continental glaciation in the Quaternary period. It is not necessary or desirable to repeat here the many lines of evidence that substantiate this conclusion, for they are found in any good textbook of physical geology. It may be said, however, that probably no part of geology offers more striking example of the results of sound deductive reasoning than the proof of Agassiz' hypothesis. The deposits of continental glaciers have foremost importance among Quaternary formations, and, as commonly defined, Quaternary time is considered to have begun with initiation of the continental glaciation that followed making of the various Tertiary deposits. This important physical event is considered to have brought the Tertiary period to a close. There is general agreement in defining Quaternary time as extending down to the present.

Divisions.—The Quaternary period may be divided into two very unequal parts: the Pleistocene epoch, comprising at least 95 per cent and probably about 98 per cent of the time of the period, and the Recent epoch, including the remainder. The term Pleistocene was introduced by Lyell in 1839 for deposits in England which he recognized as being distinctly younger than the Pliocene, and a little later this name came to be applied especially to the glacial deposits. As now defined, the

Pleistocene series includes the deposits of the Quaternary Ice Age and contemporaneous marine, fluviatile, lacustrine, eolian, and volcanic rocks. The end of the Pleistocene epoch and the beginning of Recent time may be considered to coincide with the final retreat of the ice sheets to high latitudes. That the retreat which has led to present conditions may not be "final" is ground for uncertainty as to the actual validity of the division of Quaternary time into the epochs indicated. Present practice sets off Recent time with rather unwarranted classificatory prominence. If a few thousands or tens of thousands of years in the future bring a recurrence of glacial climate with renewed invasions of continental ice sheets, obliterating cities, farms, and other works of man, it will be clear that present time should be classed as a subdivision

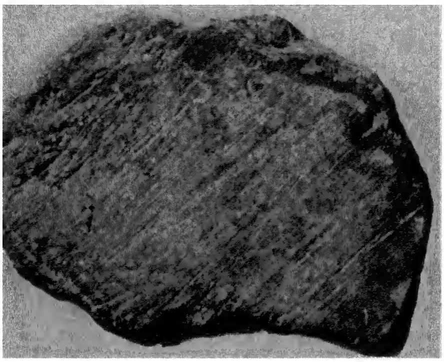

Fig. 338.—Glacially striated boulder, from Iowa (one-fourth natural size). (*U. S. Geol. Survey.*)

of the Pleistocene, which would be extended to embrace the new Ice Age. Certainly there is little to commend the practice of a few geologists in setting off Recent time as the beginning of a new era, the "Psychozoic" (soul life, in allusion to the presence of Man).

The Pleistocene glacial deposits are divisible into four main parts, which are separated by very important unconformities. These parts are the deposits of as many distinct and separate glaciations of the continent. Just as in other periods advances of the sea on the land are marked by marine deposits and the retreats by unconformities, so invasions of the Pleistocene continental glaciers are recorded over thousands of square miles by till and fluvioglacial debris, and times of deglaciation by weathering and erosion of the glacial deposits that constitute unconformities. Proof that the glacial history of the Pleistocene epoch is really complex, that there were a number of advances and retreats of the glaciers, separated by long interglacial ages, is second in importance only to the establishment of the fact of continental glaciation itself. Demonstration of multiple glaciation in the Pleistocene has come mainly

through the work of the last 50 years in the Mississippi Valley region of the United States. However, it is amply shown also in Europe and in

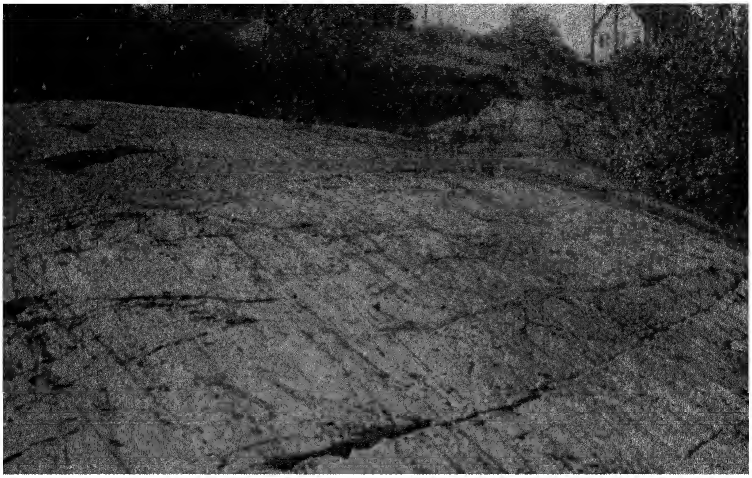

Fig. 339.—Glaciated bedrock in New England. Near Clinton, Mass. (*W. C. Alden, U. S. Geol. Survey.*)

various other places. Names of the glacial and interglacial divisions of the Pleistocene epoch are given in the accompanying table.

Divisions of the Pleistocene

Stage	North America	Europe (Alps)
Glacial	Wisconsin: Mankato Cary Tazewell Iowan	Würm
Interglacial	*Sangamon*	*Riss-Würm*
Glacial	Illinoian	Riss
Interglacial	*Yarmouth*	*Mindel-Riss*
Glacial	Kansan	Mindel
Interglacial	*Aftonian*	*Günz-Mindel*
Glacial	Nebraskan	Günz

Recent Studies on Pleistocene Classification.—The classification of the drift called Iowan has been in dispute. F. L. Leverett holds that it is more closely related to the Illinoian than to the Wisconsin, but evidence brought forward by G. F. Kay and M. M. Leighton strongly supports the conclusion that the Iowan should be regarded as an initial substage of the Wisconsin stage. Kay has recently introduced a stratigraphic grouping of glacial and succeeding nonglacial deposits to form "series" of the Pleisto-

cene "system." These are named Grandian (Nebraskan, Aftonian), Ottumwan (Kansan, Yarmouth), Centralian (Illinoian, Sangamon), and Eldoran (Wisconsin-Recent). This classification has meritorious features but its adoption will make Pleistocene synonymous with Quaternary. As pointed out elsewhere in this chapter, there is no very definite basis for separating the Pleistocene and Recent, and accordingly Kay's Eldoran series or epoch represents natural geologic relationships better than existing accepted classification.

The marine and nonmarine Pleistocene deposits of the unglaciated areas are mostly not divided on a time basis and hence a detailed chronology is here much less definitely established. It is indeed interesting to observe that the evidence for evaluation and subdivision of Pleistocene time rests wholly or almost wholly on inorganic bases rather than testimony of fossils.

Recent time is too short to have any significant basis for subdivision in a geologic sense. From an archeological standpoint there are several distinct stages in the development of man's culture that belong here, but, in Europe and Asia at least, primitive man dates far back into the Pleistocene, if indeed he did not originate before the beginning of Quaternary time.

QUATERNARY DEPOSITS AND PHYSIOGRAPHIC FEATURES OF NORTH AMERICA

Description of the chief features in the sedimentary and physiographic record of the Quaternary period in North America may be divided into parts dealing respectively with those of glacial origin on the one hand and those of nonglacial origin on the other. This division is largely a matter of convenience and it is to some extent arbitrary, as in the case of wind-blown loess, stream-borne outwash, and lake deposits that owe existence indirectly to glaciation. The intended differentiation is practically on a geographic basis: features of the glaciated territory and features of nonglaciated areas.

Glacial Deposits and Physiographic Features

Distribution

An area of about 4,000,000 square miles in northern North America, or nearly one-half of the continent, was covered by glacial ice during part of the Pleistocene epoch. The glaciated region includes almost all of Canada, Newfoundland, and Greenland and reaches southward in the Mississippi Valley region of the United States almost to the mouth of the Ohio. The southern border of the drift-covered area is roughly defined by the courses of the Ohio and Missouri Rivers.

Two chief centers of ice growth from which glacial movement radiated have been identified in North America. One of these was on the Labrador Peninsula and is known as the Labradorian center; the other was located somewhat west of Hudson Bay and is called the Keewatin center. High land south of Hudson Bay was also an important region of glacial ice formation that is designated the Patrician center. Subordinate centers

are identified in Newfoundland, Nova Scotia, and New Brunswick. The centers of radiation of the continental ice sheets are indicated partly by configuration of the glacial moraines and by evidence from striae on bedrock, and partly by lack of depositional or erosional ice action in a central area that is surrounded by marks of diverging ice movement. The centers of ice growth do not appear to have been subjected to much erosion. The mountain region of western Canada and northwestern

FIG. 340.—Map of North America showing area covered by glacial ice during some par of the Pleistocene epoch, and indicating main centers of ice-sheet growth. (*W. C. Alden U. S. Geol. Survey.*)

United States was largely buried beneath the so-called Cordilleran ic sheet. In addition to the main continental glaciation there was extensiv mountain glaciation in various ranges of the western United States.

It is interesting to note that much of western and northern Alask seems to have escaped glaciation. Also, southwestern Wisconsin an small parts of the adjoining states appear never to have been glaciated This "driftless area," over 10,000 square miles in extent, is surrounde on all sides by country that at one time or another was occupied by the ice

Evidence of Multiple Glaciation

The upper Mississippi Valley and adjacent Great Lakes region of the United States contains a remarkable record of at least four entirely distinct glaciations, of the long interglacial ages that separated the successive ice sheets, and of post-Pleistocene history. The record in this region is clearer and more complete than in any other part of North America or, indeed, of the world.

Wisconsin, Minnesota, and neighboring parts of the United States and Canada are a land of lakes, of irregular rolling and hummocky topography with variously shaped, unevenly disposed hills and intervening poorly drained depressions. Bedrock is mostly concealed by a

FIG. 341. Morainal topography near Ripon, Wis. The widespread deposits of glacial materials and the physiographic effects of glaciation are outstanding characteristics of most of the northern part of North America. (*W. C. Alden, U. S. Geol. Survey.*)

mantle of glacial till, boulders, gravel, and sand. There are drumlins, kames, eskers, outwash plains, terminal moraines, recessional moraines, and large areas of ground moraine. The insignificant alteration of this glacial topography by stream work or other erosive agencies since the time of glaciation and the lack of appreciable weathering in the materials composing the drift attest the comparative recency of glaciation.

It was naturally supposed at first that the glaciation evidenced by these well-defined topographic features and by the little-weathered till constituted the entire glacial record of Quaternary time. Increasing cold at the beginning of the Pleistocene led to the formation of an ice sheet that spread far over the areas observed to have been glaciated, and increasing warmth toward the close of the Pleistocene caused melting and disappearance of the ice sheet.

But this simple picture does not accord with observations that in Illinois, Iowa, Missouri, and other places there are widespread deposits of deeply weathered glacial till and, further, that characteristic features of glacial topography are almost lacking in these regions. Seemingly, this much-weathered drift represents a glaciation altogether different from and very much older than that marked by practically unaltered till and unmodified glacial topography. If this is the case, the older glaciation evidently extended considerably farther south than the later. Most exposures of glacial till in the north show only one drift sheet, the most recent, resting on ice-eroded bedrock. In the south, however, there are many places where one drift sheet overlies another, the contact being marked by change from the much-weathered and decayed upper

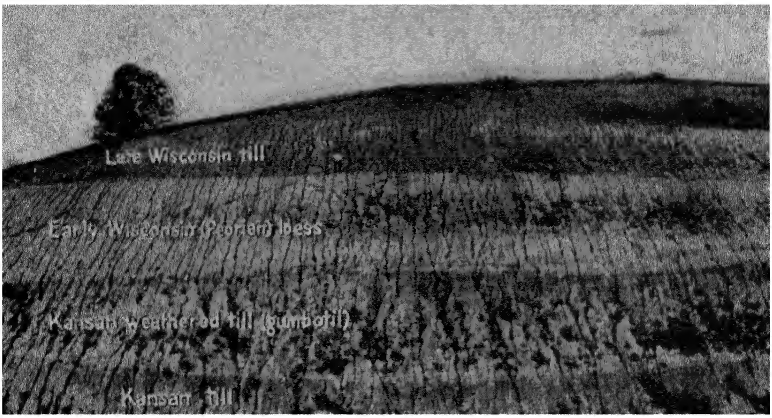

FIG. 342.—Exposure of stratified Pleistocene deposits [illegible] cut near Rhodes, Iowa. Comparatively fresh till at the top of the cut rests on loess (probably a wind deposit), and this in turn overlies deeply weathered glacial till. (*W. C. Alden, U. S. Geol. Survey.*)

portion of the older drift to the fresh, unweathered drift at the base of the overlying sheet. In places there are beds of peat and old soils, some with remains of land animals and roots of forest trees, above the older drift and buried by the younger. The later ice advance formed a veneer of deposits overlying the older but in places removed little or none of the underlying material.

Weathering of Drift.—Study of the weathering of glacial drift shows that, under influence of the dissolved oxygen and carbon dioxide in the water that soaks into the ground, there are progressive chemical changes which extend downward at unequal rates. Oxidation of iron compounds, making yellowish, brownish, and reddish colors, takes place, and more slowly there are solution and removal of calcareous material. Still slower than the leaching of calcium carbonate are the disintegration and removal of the soluble parts of silicate minerals, leaving the insoluble portions as a fine, sticky gumbo-like clay. The zones defined by these unequally

progressive chemical changes form what is called a soil profile, whose nature and thickness are a measure of the extent (and, other things being equal, the time) to which weathering has proceeded. Under topographic conditions of poor drainage, which are common in glaciated areas, the characteristic final alteration product of till is a dark, sticky gumbo-like clay, called *gumbotil*, the dark color of which is due to the reduction of the ferric iron by humic and other organic compounds derived from overlying vegetation. A gumbotil is thus a mark of very prolonged weathering of a till.

FIG. 343.—Mature stream-carved topography on Kansan drift, Union County, southern Iowa. Since the Kansan glaciation, sufficient time has elapsed to efface almost all topographic characteristics of glaciation. (*W. C. Alden, U. S. Geol. Survey.*)

The Drift Sheets and Interglacial Materials

The four main glacial divisions of the Pleistocene and evidences of the interglacial intervals that separate them will now be considered in order from oldest to youngest.

1. Nebraskan Glacial Deposits.—The oldest known glacial deposits of the Mississippi Valley region are called Nebraskan. They are seen in Nebraska, Kansas, Missouri, Iowa, and Illinois (?), but, since younger drift occurs above them almost everywhere, exposures are mainly restricted to stream valleys which have been carved in later Quaternary time. Isolated patches of deeply weathered drift and scattered erratic boulders are present in a few places outside the margin of the next younger drift sheet. The deposits left by the Nebraskan continental glacier consist of boulder clay or till and associated sands and gravels, the thickness in some places being 100 feet or more. The southern limit of the Nebraskan invasion is approximately marked by the lower course of the Missouri River. The ice that occupied the western Mississippi Valley region came from the Manitoba region or Keewatin center. The extent of the Nebraskan glaciation in the east and in the northwest is unknown, because the deposits have been subsequently obliterated or concealed, or they are as yet undiscovered or unrecognized. It is thought

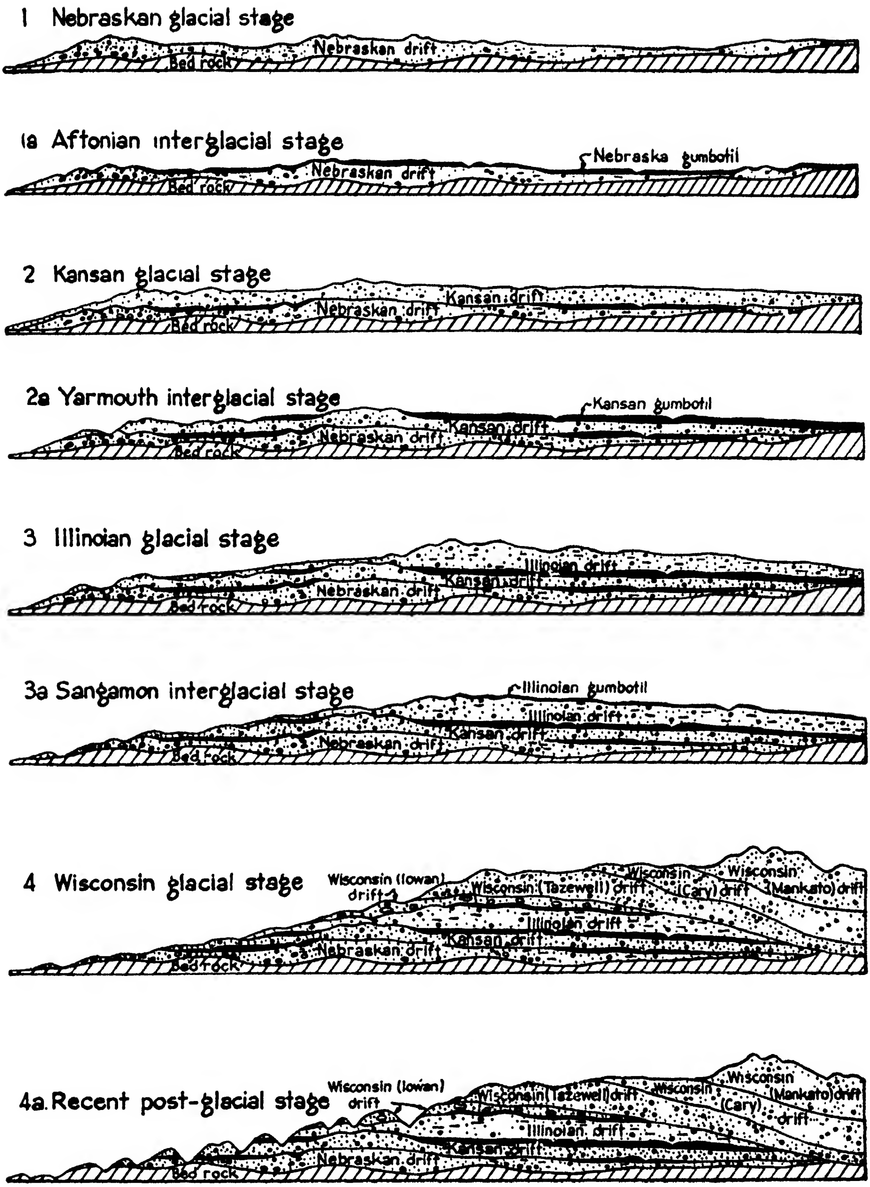

FIG. 344.—Diagrammatic sections of Pleistocene glacial deposits of the north central United States at successive stages in the epoch.

Following deposition of the Nebraskan drift (1), weathering during the Aftonian interglacial stage formed gumbotil in many places (1*a*). Advance of the Kansan ice sheet caused removal of earlier drift and gumbotil locally but in most places led to burial of Nebraskan materials under Kansan drift (2). This was followed by development of the Kansan gumbotil during the Yarmouth interglacial stage (2*a*), then Illinoian glaciation (3), formation of a thin gumbotil on the Illinoian drift in Sangamon time (3*a*), and finally the Wisconsin glaciation in which four main substages are recognized (4). Post-Wisconsin erosion has modified the surface to some extent locally but time has been insufficient for development of a gumbotil on the Wisconsin drift (4*a*). Attention is called to the fact that no single known section shows the presence of all of the Pleistocene deposits indicated in sections 4 and 4*a*.

by some that the Jerseyan drift in the east may correlate with the Nebraskan drift deposits.

Aftonian Interglacial Materials.—On retreat of the Nebraskan ice sheet, the deposits which it had formed began to be weathered. Most of the topography seems to have been that of a comparatively flat, poorly drained ground moraine plain, upon which chemical weathering was effective and erosion negligible. The weathering continued until an average thickness of more than 8 feet of gumbotil was formed by the alteration of the Nebraskan till. In places where the deposits consisted mainly of gravels, leaching of calcium carbonate extended very much deeper. There are also beds of peat, containing tree stumps and branches, and water-laid sediments, containing remains of animals that indicate a cool temperate climate.

2. Kansan Glacial Deposits.—A second Pleistocene glaciation is shown by the occurrence of till and fluvioglacial sand and gravel above the Nebraskan drift and gumbotil. The younger drift, called Kansan, occupies about the same area as the Nebraskan and is exposed not only in the sides of valleys but also on extensive upland plains, especially in northern Missouri and southern Iowa. The average thickness of the Kansan drift in this region is about 50 feet. The Kansan glacier of the western Mississippi Valley region advanced from the Manitoba region or Keewatin center, as shown by its rock constituents. An ancient drift which is known to extend far to the east, and which in central Ohio contains copper derived from the Lake Superior region, is possibly the equivalent of the Kansan. Ice from the Labradorian center reached Cape Cod and the New England islands.

Yarmouth Interglacial Materials.—After the retreat of the Kansan ice the flat, poorly drained ground-moraine deposits were subjected to weathering. An average thickness of 12 feet of gumbotil was formed on the Kansan till before the next glaciation occurred. Deposits of peat, loess, and gravel were formed in places at this time.

3. Illinoian Glacial Deposits.—The third ice sheet, the Illinoian, came from the Labradorian center and extended over a large part of Illinois, Indiana, and Ohio. A part of the lobe extended westward into Iowa, displacing the course of the Mississippi River for a time. The average thickness of the Illinoian drift is about 30 feet. Large areas of its surface are nearly flat ground moraine, but in certain belts the topography is distinctly hummocky, denoting terminal and recessional moraines. Keewatin equivalents of the Illinoian have not been recognized definitely.

Sangamon Interglacial Materials.—During the interglacial age that followed the Illinoian glaciation, the till was weathered to form a gumbotil in many places, the average depth being 4 to 6 feet. Peat and muck deposits occur locally. The prolonged period of weathering during which the gumbotil was formed was followed by a time of loess deposition,

when wind-blown materials were spread widely over the weathered Kansan drift of Iowa, Missouri, Nebraska, and Kansas and over the weathered Illinoian drift in Illinois and Indiana. Volcanic ash, interbedded with the loess, has been found in western Iowa. Calcareous materials of the loess were leached to a depth of 3 to 5 feet before glacial ice advanced again over parts of the region.

4. Wisconsin Glacial Deposits.—The youngest of the drift sheets is the Wisconsin. Its distinctive youthful features are the almost unmodi-

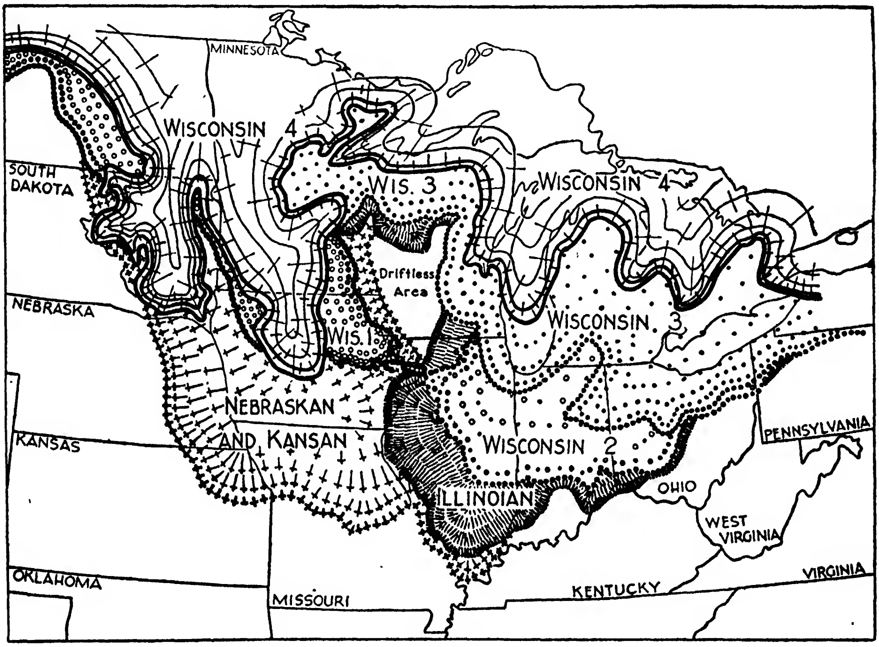

FIG. 345.—Map of the north central United States showing distribution of glacial drift of the successive Pleistocene stages.

fied glacial topography and slight weathering, which contrast greatly with the characters of the older glacial deposits. Although the Wisconsin ice did not reach as far south, in general, as preceding glacial invasions, the area covered by Wisconsin drift is much more extensive than that in which any of the older drifts are now found. The obvious reason for this is that, wherever the Wisconsin deposits occur, they overlie and conceal the older drift unless the latter was removed before deposition of the Wisconsin. The margins of the Wisconsin ice sheets were strongly lobate, as shown by the looped arrangement of the terminal and recessional moraines. The distribution of the lobes indicates that the ice movement was influenced by major topographic features of the area invaded, being accelerated by broad smooth lowlands and impeded by rough uplands. For example, it is clear that the course of the hummocky

morainal belts of the Wisconsin drift is roughly concentric with the Great Lakes depressions.

Detailed studies of the deposits of the various Wisconsin ice lobes show that the history of this glaciation is very complex. It is known that in many places the edge of the ice advanced, retreated, advanced again, receded, halted, receded, and so on, with innumerable local variations. In some cases, after the advance and partial retreat of one lobe, an adjoining lobe overrode deposits previously left by the other. It appears that in the early part (Iowan substage) of the Wisconsin glaciation the Keewatin center was most important. Later the greatest center of radiation was in the Labradorian region, from which the ice pushed southwestward as far as central Illinois; and still later the chief center of radiation seems to have shifted westward to a region (Patrician center) near Hudson Bay. The ice then advanced southward, over territory in

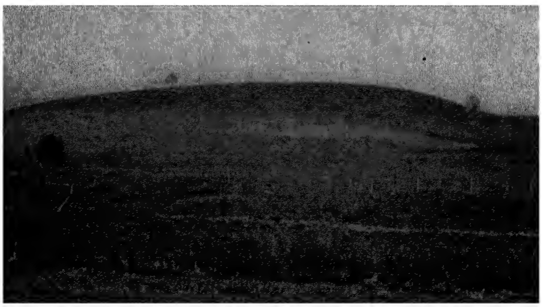

FIG. 346.—A drumlin, near Newark, N. Y. The axes of these elongate drift hills is parallel to the direction of ice movement. Wisconsin stage of the Pleistocene epoch. (*G. K. Gilbert, U. S. Geol. Survey.*)

Ohio and eastward that has not been glaciated previously, and lobes extended far to the south in Iowa and the Dakotas.

The Wisconsin glaciation was effective in cutting away the deposits of previous ice advances in many places. Where the base of the Wisconsin drift is seen, older drift is more commonly wanting than present.

The glacial deposits classed as Wisconsin include four named subdivisions: the first (Iowan) belonging to the earliest part of this Ice Age, the second (Tazewell) and third (Cary) to the middle, and the fourth (Mankato) to the last part immediately preceding Recent time. These subdivisions represent separate advances and retreats of a single great ice sheet during this glacial age. In addition to deposits made by the ice, there are associated gravel, sand, and silt deposits laid down by water and by wind.

4*a*. *Iowan Glacial Deposits.*—Glacial deposits called Iowan occur in Iowa, Minnesota, and, according to tentative correlation, in the Dakotas and northeastern Montana. They were deposited by ice lobes that

advanced southward and westward from Manitoba and southwestward from the Keewatin center west of Hudson Bay. The Iowan drift, as exposed in northeastern Iowa, has an average thickness of only 10 feet, forming thus a mere veneer of comparatively fresh till that rests on the eroded slopes of Kansan till or the deeply weathered Kansan gumbotil, or in places on post-Kansan loess.

Post-Iowan Weathering.—After the retreat of the Iowan ice, weathering of the new deposits began. Although leaching has extended down to a depth of about 6 feet, all of the time from the retreat of the Iowan

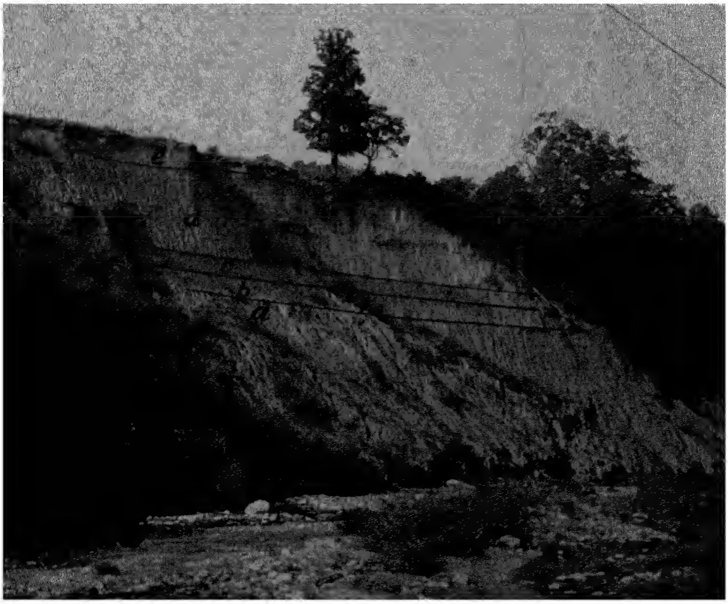

FIG. 317.—Exposure of Pleistocene beds near Peoria, Ill. (*a*) Illinoian till with mature weathering profile, (*b*) late Sangamon loess with soil and youthful weathering profile, (*c*) Peorian loess with no weathering profile, (*d*) early Wisconsin till and gravel with no weathering profile, and (*e*) early Wisconsin loess with youthful weathering profile. (*M. M. Leighton.*)

ice sheet up to the present has been insufficient to result in the formation of gumbotil. The Iowan glaciation is thus relatively recent, and much younger than the Illinoian, which, as previously noted, not only has a well-defined gumbotil but is overlaid by a well-weathered pre-Iowan loess.

Peorian Loess.—Extensive deposition of loess (Peorian) followed the Iowan glaciation. The loess is prominent near the margin of the Iowan drift sheet, where in places it forms mounds (paha hills), and it is widespread in Illinois, southern and western Iowa, Missouri, Kansas, Nebraska, and eastern Colorado. Not all of this loess is contemporaneous, however, and its sources are almost certainly of varied nature

Loess deposits are especially prominent along the main drainage lines leading away from the former ice sheet. The thickness of the loess on the borders of these main valleys is nearly 100 feet in places. The loess is clearly of wind-blown origin, as indicated by occurrence of the thickest accumulations along the tops of the bluffs and uplands adjacent to the large river valleys, and a progressive thinning away from them. Silt from multitudinous exposed dry bars and flats of the valley bottom was swirled aloft by air currents and sifted over adjacent land. Vegetation doubtless helped to hold the wind-laid materials in place. The depth of leaching in the loess corresponds closely to that observed on the Iowan

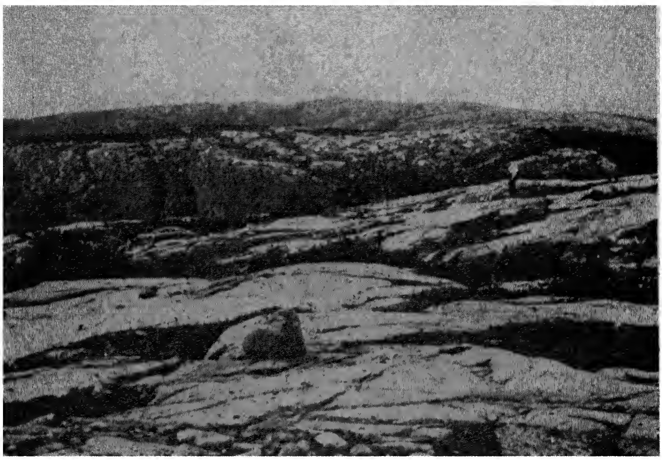

Fig. 348.—Glacial erosion has removed soil cover and rock, smoothing the upland surface in this region. Mount Desert Island, Maine. (*W. C. Alden, U. S. Geol. Survey.*)

till, which, with other evidences, shows that they are of nearly the same age.

4*b*. *Tazewell Glacial Deposits.*—The glacial drift that forms the surface of a large part of Illinois, Indiana, and southwestern Ohio is younger than the Peorian loess because it is found overlying the loess. Also, this drift which came from the Labradorian center is clearly older than the latest Wisconsin, which spread out mainly from the Keewatin center. There is not much difference in the amount of weathering shown by the early, middle, and late parts of the Wisconsin, but the topography of the Tazewell drift is more modified by erosion and there are relatively few lakes and swamps on it. Locally the terminal moraines of later Wisconsin substages cut across moraines of Tazewell age.

4*c*. *Cary Glacial Deposits.*—The drift called Cary differs from preceding divisions of the Wisconsin in the very imperfect drainage of its surface and the presence of numerous lakes and swamps in its area. This drift is identified in northern and eastern Wisconsin, around the southern tip

of Lake Michigan in the vicinity of Chicago, throughout most of the southern peninsula of Michigan, in northern Ohio, northern Pennsylvania, and New Jersey. From Ohio eastward, the Cary drift forms the southern border of the Wisconsin deposits.

4*d*. *Mankato Glacial Deposits.*—The youngest part of the Wisconsin glacial deposits, named Mankato, is least modified by weathering and erosion, although it is not strikingly different from the Cary drift. The Mankato drift is mostly poorly drained and its area contains thousands of lakes, ponds, and swamps. This drift is widely distributed west of the Mississippi Valley in Minnesota, Iowa, and the Dakotas, but it was restricted in the east to the borders of the Superior, Michigan, Huron, and Ontario lake basins and the borders of the St. Lawrence Valley. The late Wisconsin glacial deposits cover a large part of Canada.

Formation of the Great Lakes

A very interesting and important physiographic result of continental glaciation in North America was the formation of the Great Lakes, several large temporary glacial lakes now extinct, and an unnumbered multitude of smaller lakes. All of these lakes are due to the formation of depressions made by erosion or deposition of the ice or by the ponding of water between parts of the glacial ice and the adjacent land.

The recorded history of the Great Lakes began when the ice lobes retreated north of the St. Lawrence-Mississippi divide, and water from the normal drainage and the melting ice rose until it found the lowest available outlet point. The levels of water bodies thus formed were maintained until some other and lower outlet was uncovered, resulting not only in a change of level but also to some extent in outline. Shoreline features, such as beaches and wave-cut cliffs, and also lake deposits furnish evidence of the early stages of the lakes—features which are defined in proportion to the duration of the lake levels. There are physiographic evidences also in the outlets.

In addition to the effect of changing positions of the ice front, a general slow tilting of the land surface has had important influence on the history of the lakes. Under the enormous weight of the continental ice sheet which was thousands of cubic miles in aggregate volume, the northern part of the continent was considerably depressed. With the removal of the ice by melting there was a somewhat resilient upbowing of the land. This upward movement was slow and there is evidence that it may still be in progress. The rise has been least in the south and southwest and greatest in the northeast, where in places it amounts to some hundreds of feet. The differential nature of the warping is clearly defined by the gently tilted attitude of the lake beaches, which were horizontal originally. The main steps in the development of the Great Lakes are given in the following summary and accompanying maps.

1. Formation of lakes at the tip of the Michigan and Erie ice lobes; outlets by way of Illinois-Des Plaines and Wabash rivers to the Mississippi (Fig. 349).

2. Retreat of ice, forming larger lakes, especially in the Erie basin; abandonment of Wabash River outlet because of the uncovering of a new outlet that drained waters of the Erie basin northward into a lake

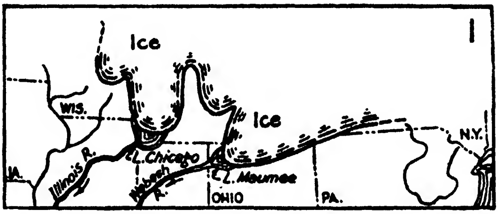

FIG. 349.—A very early stage in the formation of the Great Lakes. (*Modified from Taylor and Leverett, U. S. Geol. Survey.*)

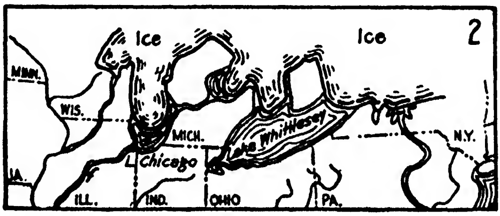

FIG. 350.—Lake Whittlesey stage in the formation of the Great Lakes. (*Modified from Taylor and Leverett, U. S. Geol. Survey.*)

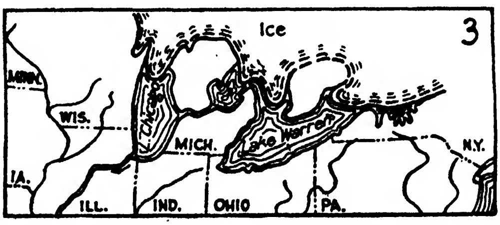

FIG. 351.—Lake Warren stage in the formation of the Great Lakes. (*Modified from Taylor and Leverett, U. S. Geol. Survey.*)

formed at the tip of the Saginaw ice lobe and thence by way of Imlay and Grand Valleys westward across Michigan (Fig. 350).

3. Slight retreat of the Huron lobe causing further lowering of the lake in the Erie basin to the level of a lake in the Huron-Saginaw basin with which it was confluent; drainage westward into the Lake Michigan basin and southwest to the Mississippi (Fig. 351).

Readvance of the Huron ice lobe, separating the Huron-Erie waters from those of Saginaw, raising the lake level of the former but not the latter.

4. Retreat of the ice, causing the beginning of a lake in the Superior basin and opening outlet for waters of the Huron-Erie basin by way of Mohawk River into the Hudson; outlet of the Lake Michigan basin still southwestward from Chicago (Fig. 352).

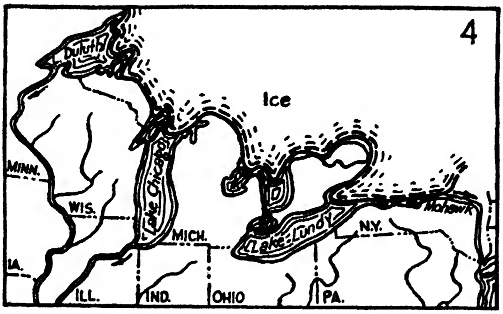

FIG. 352.—Lake Lundy stage in the formation of the Great Lakes. (*Modified from Taylor and Leverett, U. S. Geol. Survey.*)

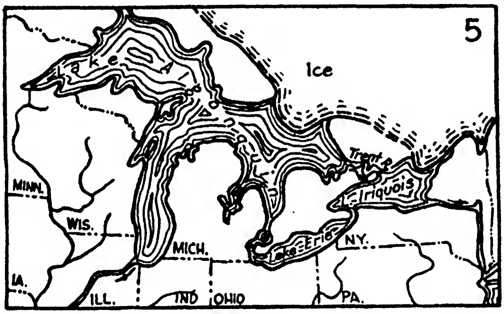

FIG. 353.—Lake Algonquin stage in the formation of the Great Lakes. (*Modified from Taylor and Leverett, U. S. Geol. Survey.*)

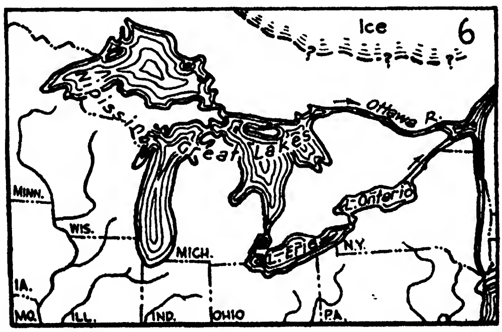

FIG. 354.—Nipissing Lake stage in the formation of the Great Lakes. (*Modified from Taylor and Leverett, U. S. Geol. Survey.*)

5. Retreat of the ice, uncovering almost all of the Great Lakes area, with drainage of Lake Erie northward into the Ontario basin. The three upper Great Lakes of the present were combined in a single large water body which drained eastward across Ontario by way of the Trent River

Valley, thence eastward by way of the Mohawk. Some water may have been discharged to the outlet at Chicago during part of this time (Fig. 353).

6. Complete withdrawal of the ice from the lakes region, disclosing an outlet for the upper lakes by way of Ottawa River directly to the St. Lawrence. This region in the northeast was much lower than now, the sea extending into the Champlain Valley and Lake Ontario basin (Fig. 354).

7. Differential elevation of country in the north, causing abandonment of the Ottawa River outlet and introducing present conditions (Fig. 355).

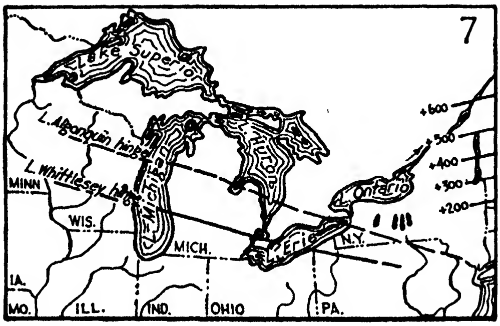

FIG. 355.—Present Great Lakes, showing position of hinge axes of the Whittlesey and Algonquin stages. The land northeast of the hinge-lines has been differentially upwarped as a result of removal of ice load by melting. Figures at right indicate amount of uplift in feet. (*Modified from Taylor and Leverett, U. S. Geol. Survey.*)

Retreat of the ice from the Red River basin northwest of Lake Superior produced a lake (Lake Agassiz) which vastly exceeded in dimensions any of the existing Great Lakes. It is marked by lake deposits and well-formed beaches. The lake drained southeastward by way of valleys now occupied by the Minnesota and Mississippi Rivers. Eventually, when the ice retreated far enough north to permit discharge of waters into Hudson Bay, the lake was drained, except for its present remnants, Lake Winnipeg, Rainy Lake, and other smaller water bodies.

Recent Materials

In the time since the ice disappeared from the northern United States, leaching of the calcareous materials in the Wisconsin drift has extended downward about 2½ feet. Deposits of innumerable lakes, swamps, and streams have been made since the glacial ice vanished. Locally, as at the south end of Lake Michigan, sand dunes occur.

Mountain Glaciation

During the Pleistocene epoch, large quantities of snow and ice accumulated in mountain ranges of the western United States and Canada.

Mountain glaciation occurred on a large scale. At times of maximum growth the glaciers scoured out and considerably deepened gorges previously cut by the mountain streams. Tongues of ice reached many miles down the valleys and in places spread out as lobes on the adjacent lowlands, building great lateral and terminal moraines. Many topographic features in these mountain areas where ice is now absent are due to Pleistocene glaciation. The effects of glaciation are recorded as far south as Arizona and southern California.

Multiple Glaciation.—Early drift (Nebraskan or Kansan) lies on remnants of a piedmont terrace bordering the Rocky Mountains in Montana. The elevation of the drift-bearing terrace is as much as 1,000 feet above the present drainage. Much younger glacial deposits (Wisconsin) and, in places, also some drift of Illinoian (or Iowan) age are found in the lower parts of the valleys, which, subsequent to the early glaciation, were cut down much below the high terrace levels. Both Wisconsin and pre-Wisconsin glacial deposits occur in intermontane basins farther west. Three and possibly four glaciations are recognized in the mountains of western Wyoming. The oldest deposits lie on remnants of high piedmont terraces. These remnants are separated by valleys that have been carved in places 1,000 feet in bedrock since this early glaciation. Later drift deposits occur in the lower part of the valleys. The San Juan Mountains of southwestern Colorado likewise show clear evidence of at least three glaciations (probably Kansan, Illinoian, and Wisconsin). The Sierra Nevada Mountains and many other places show evidence of two or more glaciations. The glacial deposits of different age are in each case recognized by their topographic distribution and by relative weathering.

Nonglacial Deposits and Physiographic Features

Prominence is rightly given to the occurrence and effects of glaciation in study of the Quaternary period. It must not be forgotten, however, that the glaciated territory in North America comprises less than one-half of the continent and that, as regards the whole world, effects of glaciation are restricted to a relatively small fraction of the land surface.

The unglaciated regions contain many kinds of deposits and numerous physiographic evidences of conditions in Quaternary time leading up to the present. The history of older periods must be deciphered almost wholly on the basis of the nature, fossil content, and structure of deposits formed during these periods. The physical environment in which the sediments were formed is necessarily based largely on inference. The record of Quaternary time, on the other hand, is so recently inscribed that not only are the deposits clearly preserved but also the environment in which they were made. The configuration of the land surface, as developed by agencies of both erosion and deposition, is approximately

equal in historical significance to the Quaternary deposits themselves. Physiography can hardly be dissociated from the sedimentary record.

Quaternary formations and surface features formed in this period are the results of work of the wind, running water, ground water, lakes and swamps, the sea, and organisms living on land or in the sea. In addition, the effects of crustal movements and vulcanism are important. There is space here for only a very brief survey of these evidences, which may be taken up by regions.

Atlantic Border.—The Atlantic Coastal Plain from New Jersey to Florida is covered by an extensive veneer of Quaternary deposits consisting of clay, loam, sand, gravel, and peat or swamp muck; and in parts of the north there are scattered ice-floated boulders. These deposits

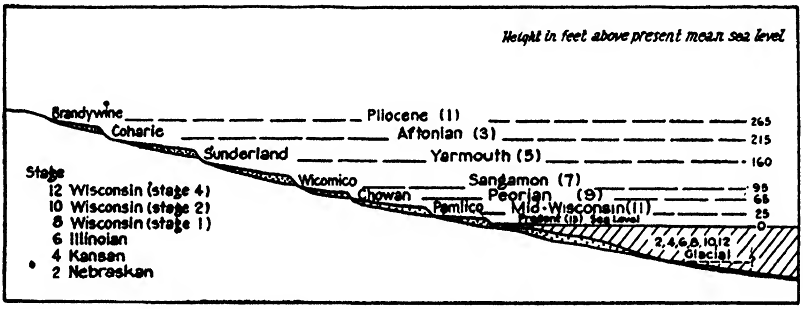

FIG. 356.—Marine terraces on the Atlantic Coastal Plain and tentative correlation with stages of the Pleistocene epoch. During glacial stages when great quantities of water were abstracted from the ocean basins to make ice sheets, sea level was lowered, but during interglacial warm stages the water was largely returned to the oceans, raising the sea level. (*After C. W. Cooke, U. S. Geol. Survey.*)

(called Columbia in Maryland, Virginia, and adjacent regions) largely conceal older formations on the interstream areas and are chiefly confined to the lower parts of the plain, or below an elevation of about 250 feet. They are found in various places resting unconformably on all of the older Coastal Plain formations to the pre-Cambrian. The deposits are of both nonmarine and marine origin, the latter especially being divisible into a number of formations defined by physiography rather than differences in composition or character of fossils. There is clear evidence, consisting of well-defined terraces carved and built by the sea at different levels, showing that at different times in the Quaternary period the level of the sea was higher than now. The deposits of these terraces are the separate named Quaternary formations, the oldest being found at the highest levels and the successively younger ones nearer the sea. Marine deposits classed as Recent are now being built as a terrace, the top of which is at sea level. Unlike the Tertiary and Cretaceous formations of the Coastal Plain, which continue uninterruptedly seaward from their outcrops, the Quaternary terrace formations are discontinuous seaward. The Quaternary formations terminate at the inner edge of the next lower

terrace, and each terrace formation consists of the reworked materials of higher terraces and of the underlying Tertiary or Cretaceous sediments. Beneath the present sea, however, Quaternary sediments of the same age as the various terrace deposits probably exist.

In addition to the deposits laid down on the submarine portion of the Coastal Plain and in estuaries and streams, there are large accumulations of sand in beaches, bars, spits, and dunes. Deposits of organic matter occur in the peaty muck of marshes and swamps and in the humus of soils.

A considerable part of Florida is mantled by Quaternary marine limestone of shelly, oolitic, or marly character. Similar deposits are being formed offshore at the present time. In addition, there are large coral reefs.

Gulf Plains.—Quaternary deposits and physiographic features of the plains region bordering the Gulf of Mexico are essentially comparable to those along the Atlantic Coast. A belt of marine Pleistocene sand and clay, 15 to 20 miles wide, occurs along the Gulf shore in northwestern Florida and southern Alabama in addition to the terraces at different levels above the sea. Along the Louisiana and Texas coast west of the Mississippi, a flat lowland, 50 to nearly 100 miles wide, is composed of Quaternary clay deposits (Beaumont and Port Hudson) with some sand and calcareous material. As shown by well records, the thickness of the Quaternary deposits in some places is 800 feet, and in at least one locality near the Texas-Louisiana line more than 2,000 feet, as is shown by a boring that encountered Recent cypress wood at that depth. This shows that the coastal region has progressively sunk as new deposits of sediment were formed. There are terraces at different levels, but these have not been correlated definitely with those of the Atlantic Coast region.

Stream deposits form a very important part of the Quaternary deposits in the Gulf region, for they comprise not only the great delta and flood plain of the Lower Mississippi but alluvial deposits of many other streams. During Quaternary time the Mississippi Delta has been built seaward not less than 125 miles. The materials of the surface parts of the delta and flood plain of this and other streams, and the development of most of the distinctive physiographic features of the region, are of recent origin.

Along the coast, especially in Texas, are long barrier reefs of sand.

Appalachian Region.—The portion of the Appalachian mountain and plateau region south of the ice border contains few Quaternary deposits except alluvium in the stream valleys. Erosion rather than deposition has been dominant during this period. A relative lowering of the position of sea level has caused deepening of stream valleys below the broad flat valley bottoms that had been developed in Tertiary times. Numerous drainage changes are evidenced in the country adjacent to the glaci-

ated area, especially in western Pennsylvania, West Virginia, and Kentucky. In some places there are very thick deposits of gravel, sand, and clay that were formed by the blocking of valleys by ice or by accumulation of glacial materials. The Ohio River, which follows roughly the southern border of the glaciated area, was formed during Quaternary time, partly by diversion of former north-flowing streams and partly by the combining-together of several formerly separate drainage lines. As a result, the Ohio Valley is wide in places and very narrow in others, and the yet unadjusted stream gradient changes in different sections from 0.5 to over 5 feet per mile.

A minor but interesting geologic feature that belongs largely if not wholly to the history of Quaternary time is the formation of large caverns, such as Mammoth Cave in Kentucky, and their associated stalactitic and stalagmitic deposits. A number of the caves contain skeletal remains of Pleistocene animals that are now extinct.

Central and High Plains.—Stream deposits of valleys, terraces and uplands, and wind deposits, including loess and dune sand, are the chief Quaternary materials of the plains region south of the glaciated territory. Part of the calcium carbonate-cemented sand and gravel that mantle so great a part of the High Plains east of the Rockies is undoubtedly of Pleistocene age, as is indicated by animal remains contained in these deposits. The calcium carbonate is carried by percolating ground water and deposited from it by evaporation, forming *caliche*. In this way it makes a cap rock that retards stream erosion and serves to preserve great areas of featureless plains, as especially well shown in western Kansas and northwestern Texas.

There have been some readjustments of drainage in this region, but they are not striking. The course of the Missouri River seems to have been established in much the same way as that of the Ohio, by diversion and compounding of preexisting drainage near the ice border.

Rocky Mountain Region.—Besides the glacial features already noted, the Rocky Mountain region contains numerous marks of Quaternary time. Most of the sculpture that gives the mountains and canyons their present form belongs to the Quaternary period. It is even possible that the last of the great recurrent uplifts that have rejuvenated the range belongs near the beginning of Pleistocene time. Nonglacial Quaternary deposits in this region include huge quantities of boulders, gravel, sand, alluvium, clay, and other constituents of the innumerable talus slopes, alluvial cones and fans, valley bottoms, lake beds, landslides, and spring deposits. Formation of all of these is taking place at the present time. Recent earthquakes, and slight movements along Pleistocene and Recent faults, indicate that mountain-making is still in progress.

Colorado Plateau and Great Basin.—Evidences of erosion and deposition in Quaternary time are shown on a grand scale in the Colorado

Plateau and Great Basin region. Hundreds of miles of deep, narrow canyons, some of them thousands of feet in depth, have been largely or wholly carved during this period. Most of the erosion of the Grand Canyon in Arizona is of Quaternary date. Wind, as well as running water, has been important in molding the landscape.

The deposits of streams and sheet wash vastly predominate over those of lakes, wind, and other agents of sedimentation. The unconsolidated materials in the present stream valleys are almost wholly of Recent origin. The large depressions between the many mountain ranges of the Great Basin are deeply filled with water-borne waste, much of which is of Pleistocene age. The thickness of Quaternary sediments is measured locally in thousands of feet. Boulders, cobbles, and finer detritus are carried downward from the mountains by occasional torrents

FIG. 357.—Shore terraces of Lake Bonneville, near Provo, Utah These terraces and the remnants of high-level deltas show the existence in Pleistocene time of a water body many times greater than the modern Great Salt Lake. (*W. C. Alden, U. S. Geol. Survey.*)

and deposited in rudely stratified fans sloping toward intermontane depressions that may be occupied temporarily by shallow lakes (playas). Evaporation of the water may leave deposits of salt.

The Great Basin contains many subordinate basins in which are found shallow temporary or permanent lakes, most of which are saline or alkaline. The largest of these lakes is the Great Salt Lake in Utah. Greatly increased precipitation in this region during parts of Pleistocene time caused such increase in size of the lake that the waters of different basins became confluent. A very large lake thus formed in Utah is known as *Lake Bonneville*. At one time this water body had a maximum depth of about 1,000 feet and covered 19,000 square miles. It was then a fresh-water lake, for an outlet was established northward into Snake River. Subsequently, with increase of evaporation over precipitation, the lake level sank lower and lower, size dwindled, and the water became increasingly salty. Great Salt Lake, the diminutive descendant of Lake Bonneville, has a maximum depth of less than 50 feet and an area of about 1,800 square miles. Large quantities of salt have been deposited

in parts of the Bonneville basin and the existing lake is a brine containing more than 400,000,000 tons of dissolved salt. Former lake levels are clearly marked by beaches and wave-cut cliffs and by large deltas of sand and gravel that were built out into the lake at the mouths of inflowing streams. These features and the flat topography of the old lake bottom are very striking characters of the landscape near Salt Lake City, Provo, and other cities of the Salt Lake Valley. A similar large Quaternary lake in west central Nevada is known as *Lake Lahontan.* An interesting deposit formed in parts of these lakes is large masses of calcareous tufa.

Pacific Border.—The Pacific Border region, in which may be included the Sierra Nevada, Cascade, and Coast Ranges, the Great Valley of

Fig. 358.—The glacially scoured valley of Yosemite, Calif. (*F. E. Matthes, U. S. Geol. Survey.*)

California, and the Coastal belt, contains in places very thick accumulations of Pleistocene and Recent fluviatile gravels, sands, and clays, as well as marine deposits near the coast that in places are nearly a thousand feet above present sea level. Diastrophic movements involving folding and faulting of the rocks, accompanied by earthquakes, have been so numerous in late geologic time that the region is undergoing change from this cause almost continuously. Steeply tilted and faulted Pleistocene beds are found. Narrow coastal plains which are found in some places are recently elevated portions of the sea floor.

Evidence of stream work, so exceptional in character as to seem incredible, is found in the Columbia Plateau region of eastern Washington, which has become known as the *Scablands.* Along a plexus of drainage ways, the upland loess, 100 to 300 feet thick, has been swept away by

running water; the underlying bedrock has been carved into canyons which are hundreds of feet deep and contain in places deep water-filled depressions; there are huge abandoned waterfalls; and where deposition occurred, the materials are found to consist mostly of coarse, little-rounded gravel and cobbles built in bars up to 400 feet high. The relation of all these features is such as to suggest that the cause was a short-lived flood of enormous volume, sufficient to have had a depth locally of more than 400 feet and to have eroded and deposited in an unprecedented scale and manner. The inferred flood has been called the Spokane flood (Bretz). It was possibly produced by the sudden emptying of a large body of impounded water, such as glacial Lake Missoula, by a retreat of ice that had blocked the outlet. It is also possible that there was a succession of such floods, as from the breaking of temporary ice dams, and that a longer and more complicated history is involved.

QUATERNARY DEPOSITS OF OTHER CONTINENTS

Europe.—The glacial and other Quaternary deposits of Europe have been much studied, but, on the whole, conditions are less favorable for detailed differentiation

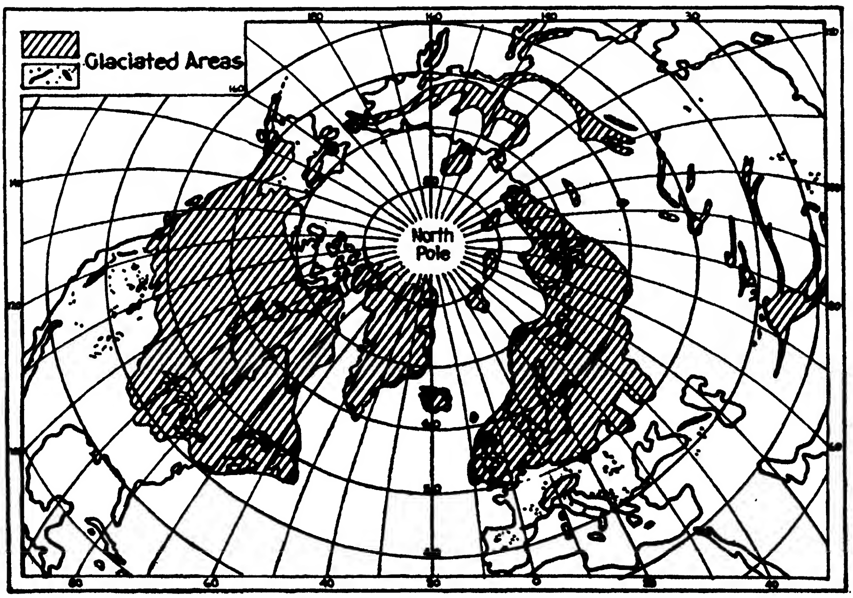

Fig. 359.—Map of the Northern Hemisphere showing areas glaciated in the Pleistocene epoch. The ice sheets of northern Europe were smaller than the North American glaciers. (*After E. Antevs.*)

of the deposits and delineation of corresponding history than in America. In the Alps region, evidence is found of four distinct glacial ages separated by interglacial ages. In order from oldest to youngest the glacial ages are designated Günz (equivalent to Nebraskan), Mindel (Kansan), Riss (Illinoian), and Würm (Wisconsin). Deposits of continental ice sheets representing three and possibly four stages are found in northern Germany, Poland, Russia, Finland, Scandinavia, and the British

Isles. Names applied to these drift sheets in northern Europe are (1) Älteste, (2) Elster, (3) Saale, and (4) Weichsel (Woldstedt). The earliest of the three definitely recognized drift sheets, classed as Elster (Mindel), is the most extensive, while the intermediate Saale (Riss) covers a larger territory than the youngest, or Weichsel (Würm). The center of radiation was in the Scandinavian Peninsula. During some of the Pleistocene glaciation, ice extended from Scandinavia across the North Sea to the British Isles, carrying boulders derived from the Scandinavian rocks, but in the last glacial stage there were local centers of ice growth in Great Britain.

Well-defined terraces at different elevations are present in parts of Europe, especially along the Mediterranean Sea. These terraces are comparable to those described along the Atlantic Coast in North America and are evidently of similar origin. The nonglacial marine and nonmarine Quaternary deposits that are found in Europe are essentially similar to those in America.

Asia.—Extensive mountain glaciation occurred during the Pleistocene epoch in the great mountain ranges of Asia, like the Caucasus, the Himalayas, Tian Shan, and others. A continental ice sheet covered part of northern Siberia. Western China and Mongolia contain extremely thick deposits of loess, which are world-famous. Some of the great rivers of Asia, such as the Yangtze-kiang, Hwang Ho, Brahmaputra, and Irrawaddy, have built tremendous alluvial deposits during Quaternary time. The intensely cultivated fertile plains made by these streams support a denser human population than any other part of the world. Pleistocene deposits rich in fossil bones have recently been discovered in the Gobi Desert region by an expedition of the American Museum of Natural History.

Other Continents.—Excepting Antarctica, which is ice-covered today, no other continents contain important Quaternary glacial deposits, although there are evidences of mountain glaciation in all of them. Nonglacial deposits are varied and widespread. They include, for example, the enormous dune sand areas of the Sahara, river deposits of the Nile, Niger, and Congo in Africa, the Amazon, Orinoco, and La Plata in South America, and the coral limestone of the Australasian region.

PHYSICAL HISTORY OF QUATERNARY TIME

As indicated by characters of the deposits and physiographic features that have been described, we may now summarize the physical history of Quaternary time in North America.

Pleistocene Epoch

The beginning of Pleistocene time is marked by the appearance of the first of the continental ice sheets (Nebraskan) of later geologic time. Accumulation of snow and ice proceeded gradually until a vast glacier was formed, spreading southward some 1,500 miles to points slightly south of the Missouri River in Missouri. The ice appears to have advanced over a maturely drained region of moderate relief. When, at length, decreasing frigidity caused the ice to dwindle and disappear, a widespread mantle of till and of fluvioglacial gravel, sand, and clay was left behind, the latter extending far beyond the glacial border as well as covering parts of the area within it. The climatic changes that led to glaciation must also have affected in varying ways and degrees the unglaciated parts of the continent. Removal of ocean water aggregating millions of cubic miles in making the continental glaciers undoubtedly

lowered the sea level appreciably. Of great importance also was the loading effect of the ice sheet, which in the last glaciation is known to have depressed the northern part of the continent considerably. These changes of the strand line must at least have influenced erosion and deposition in the coastal belts and may have affected conditions inland. Acceleration of stream erosion and deposition in different places may be inferred where precipitation was notably increased and where large quantities of water were furnished by melting of the ice. Beginning of the fluctuations of lakes in the Great Basin and of the formation of the Great Lakes depressions may belong here.

With the disappearance of the Nebraskan ice sheet, conditions returned to "normal," and for a very long period, aggregating apparently some hundreds of thousands of years, there was little important change. The Nebraskan drift became more and more deeply weathered, until in the flat, poorly drained areas several feet of gumbotil were formed. There is evidence that during much of this time the climate was even warmer on the average than now. The glacial waters were returned to the seas, causing a rise of sea level. Removal of the ice load permitted readjustments in the earth's crust in the direction of preglacial conditions, that is, a rise of the land surface in the north and a relative depression in the south. Elevation of the sea level along the Atlantic and Gulf Coasts and less definitely along the Pacific Border is marked by high terraces and terrace deposits.

The successive later chapters of Pleistocene history essentially repeat the characters of the first. Return of cold led at length to the formation of another huge ice sheet (Kansan) which spread southward over much the same area and to about the same distance as the first glaciation. With the retreat of the ice came a long time of genial warm climate (Yarmouth); again glaciation (Illinoian) and a long interglacial age (Sangamon). The last glacial age (Wisconsin) may be considered to have begun when the ice sheet called Iowan appeared. The invasion of this glacier did not last long. It was followed by extensive loess deposition (Peorian). The ice sheet spread southward again (Tazewell substage), the movement coming mainly from the Labradorian center and south of Hudson Bay. A partial retreat of the ice margin followed, then another advance (Cary substage). Again came a time of recession, and a final advance (Mankato substage), moving especially southward and westward from the Manitoba region. As has been noted in describing the deposits, the last glaciation is responsible for most features of the land surface in the northern part of the continent. To the late part of the Wisconsin glacial age belongs the formation of the Great Lakes with the several steps that mark temporary levels and drainage outlets; also the formation of the great temporary Lake Agassiz. The final part of the evolution of the Great Lakes probably belongs to Recent time.

Recent Epoch

With the disappearance of the last continental glacier, Recent time may be considered to have begun.[1] This is not a very definite or sharply drawn division line in Quaternary time, as it is not known how long remnants of the ice sheet persisted. There is a tendency among some geologists to regard Recent time as beginning with the disappearance of the ice at a given point in which they are interested. Thus, Iowa geologists may consider that the Recent epoch began when the Wisconsin ice uncovered Iowa, whereas Canadian geologists may well insist that

FIG. 360.—Flat-top peneplain in the Colorado Rockies. This erosion surface, formed during Tertiary time, has been elevated to a height of more than 13,000 feet above sea level, the last upward movement possibly belonging to the Pleistocene epoch. (*W. T. Lee, U. S. Geol. Survey.*)

the beginning of Recent was subsequent to the retreat of glacial ice from southern Canada. This is hardly satisfactory, since what is called Recent in southern areas would begin several thousands of years before that of northern districts. The pertinent conclusion is that there is no sharp line of demarcation between Pleistocene and Recent. By study of seasonal bands of glacial lake clays, the rate of retreat of the Wisconsin ice sheet has been determined to be about 1 mile in 10 years. However, there were temporary halts when recessional moraines were built, and it is probable that the later rate of retreat was considerably accelerated.

Postglacial erosion and deposition by various geologic agencies are slight but appreciable in some places where the time in which the work

[1] Schuchert and some other writers define the beginning of the Recent epoch as the time when the late Wisconsin ice sheet, having reached maximum spread, started to recede. This definition, which makes Recent time largely glacial, is arbitrary and poorly accordant with the philosophy of geologic time classification. On the other hand, it may be argued that glacial (hence, Pleistocene) conditions persist today and that Recent, if recognized at all, should be classed as a part of the Pleistocene. The "Ice Age" has surely not vanished in Greenland and Antarctica.

was accomplished is determinable. For instance, in several cases it can be ascertained that gorges have been cut since the time of glaciation. In most places outside the glaciated territory it is not possible to discriminate between effects of erosion and deposition belonging to Recent time and those of late Pleistocene age. This is true also in some degree of marine deposits. Delineation of details of Quaternary history is based largely on physiographic studies.

Volcanic Activity

We have seen that the record of Quaternary time is by no means written alone in terms of the work of ice and snow. In addition to changes effected by agents of erosion and sedimentation, evidences of

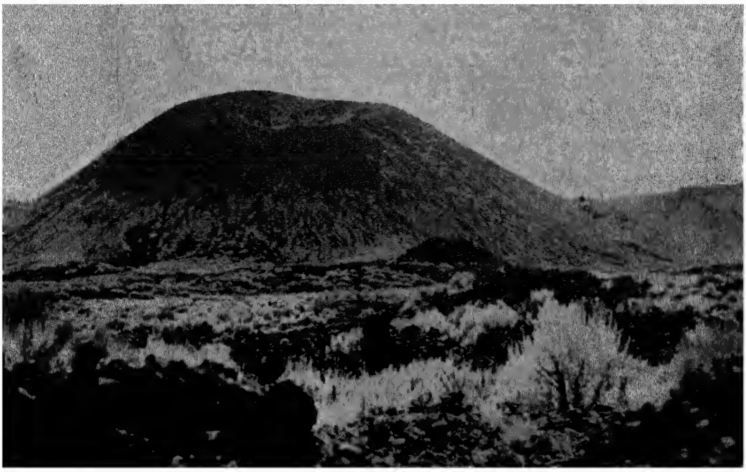

FIG. 361.—A cinder cone of geologically very recent origin, in Diamond Valley, southwestern Utah. (*W. T. Lee, U. S. Geol. Survey.*)

vulcanism are to be noted. Igneous rocks of Quaternary age are not all clearly differentiated from those belonging to the late part of the Tertiary, but in the western part of the continent there are many extensive lava flows and numerous cinder cones that are clearly very recent. These occur in Mexico, California, Arizona, New Mexico, Colorado, Utah, Nevada, Oregon, Washington, Idaho, and western Canada. Evidence of Quaternary age is found in the relation of the extrusive igneous materials to Pleistocene or Recent sedimentary deposits and in physiographic characters. The lava covers comparatively recent alluvium of stream valleys in a number of cases. Frequently the surface of the solidified lava shows ropy structure and other features identical with recently congealed flows of the Hawaiian and other volcanoes. There is little or no soil, and vegetation has as yet not been able to gain a foothold upon

the lava. Cinder cones appear as though they were formed but yesterday and might at any time resume their growth. The large volcanic mountains, like Mounts Rainier, Hood, and Shasta, are evidently of pre-Quaternary origin, although lava flows of postglacial date are recorded on Mount Shasta. Another California peak, Mount Lassen, became explosively active in 1914 after a quiescent period of unknown duration. Active volcanoes are found along the Pacific Border in Alaska, Mexico, Central America, and South America.

An unusually interesting volcanic eruption of Quaternary age is seen in the lower part of the Grand Canyon of the Colorado. Streams of lava poured forth on the rim, cascaded to the bottom of the gorge, and flowed downstream for a distance of fully 70 miles. The flow that extended down the canyon was relatively a mere thread, 300 or 400 feet in width and about 100 feet in depth, and the fact that the even top of the flow maintains about the same height above the present river and the great length of the lava tongue shows strikingly the fluidity of the flow. The vigorously eroding river has now cut away most of the flow, but remnants still cling to the canyon walls

Duration of Quaternary Time

Many efforts to compute the duration of parts or all of Quaternary time have been made. Various methods have been employed, some worthy of credence, others little more than guesses.

Evidence from Weathering of Drift Sheets.—The best available measure of the duration of Pleistocene time seems to be that based on depth of leaching and decomposition of the materials of the drift sheets. For example, if calcareous constituents of the late Wisconsin (Mankato) drift have been leached to an average depth of 2½ feet in the time since this glaciation, the observed average depth of leaching in the Iowan drift of 5 to 6 feet may be interpreted to mean that the time since the Iowan glaciation is slightly more than twice as long as that since the late Wisconsin. If the rate of leaching is slightly slower at increasing depths, the value assigned to post-Iowan time must be proportionately increased. Gumbotil, the ultimate product of chemical decay of till in flat, poorly drained areas, is found at the top of the Illinoian, Kansan, and Nebraskan tills but not on the Wisconsin tills, even where the topographic conditions are favorable. Evidently, gumbotils do not begin to be formed until there has been time for leaching of calcium carbonate to a depth of at least 6 feet. A measure of the time value of gumbotils of various thicknesses is found in the depth of leaching of gravel deposits of the same age as the gumbotil. For example, while 12 feet of Kansan gumbotil was being formed, upland gravels of the same age and in similar topographic and climatic conditions were leached to a depth of 30 feet. Study of these results of weathering of the drift leads to the following determination (G. F. Kay) of the minimum comparative time values represented by the weathering. If the time since maximum spread of the late Wisconsin (Mankato) ice is designated as 1, then post-Iowan time

is about 2.2, Sangamon interglacial time is about 4.8, Yarmouth interglacial time 12, and Aftonian interglacial time 8. To convert these values to years, we must know as accurately as possible the time value of 1; and to derive a figure for the duration of the Quaternary period, the time involved in the glaciations must be added to the figures for interglacial and postglacial times.

Evidence from Recession of River Falls.—Attempts have been made to measure the time since the Wisconsin ice retreated from the northern

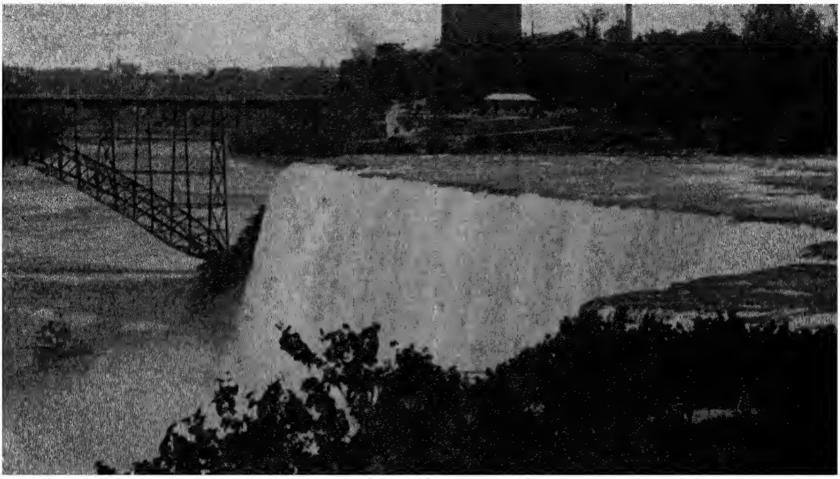

FIG. 362.—Niagara Falls, looking northeast from Goat Island. The recession of the falls furnishes a measure of the lapse of postglacial time. This photograph was made after the fall of rock in January, 1931, that changed the outline of the crest. (*Courtesy New York State Reservation at Niagara.*)

United States by study of the rate and total amount of the recession of certain river falls that came into existence immediately after the last glaciation. Chief of these are Niagara Falls and St. Anthony Falls, the latter on the Mississippi River at Minneapolis.

The beginning of Niagara Falls can be dated at the time when the Wisconsin ice retreated north of the escarpment of Niagaran limestone in western New York. Drainage from streams, lakes, and part of the ice front to the west followed the present course of Niagara River and tumbled over the escarpment near the town of Lewiston. From this point the falls have subsequently receded about 7 miles to their present position, forming Niagara Gorge. Dividing the total length of the gorge by the present average annual amount of recession, which is fairly accurately determined at 3.8 feet, the length of time required for the making of the gorge is figured to be about 10,000 years. This method of computation is inaccurate and gives a value far too low for postglacial time. The observed recession rate of the falls depends on the volume

of the discharge of the present Niagara River which drains all of the Great Lakes above Ontario. During much of the past when the waters of Lakes Huron, Michigan, and Superior had a different outlet, the flow of Niagara River was correspondingly reduced, and the rate of recession of the falls greatly retarded. All of the evidence being taken into account, estimates of the time required for the recession of Niagara Falls from its original position range from 20,000 to 39,000 years.

Saint Anthony Falls originated near the present confluence of the Mississippi and Minnesota Rivers, where the waters of the newly formed Mississippi were precipitated into a broad valley that had served as the outlet for glacial Lake Agassiz in the North Dakota-Manitoba country.

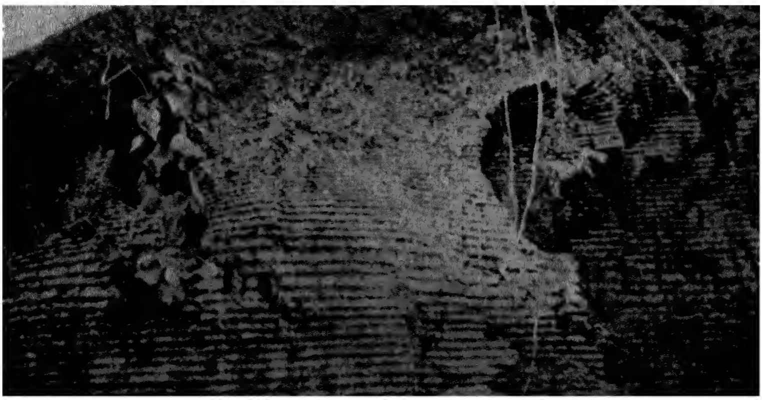

FIG. 363.—Pleistocene banded clay deposits near Timmins, Ontario. Each pair of light and dark clay layers is termed a varve and this marks the deposition of one year. (*E. Antevs, Geol. Survey Canada.*)

The minimum time required for the recession of these falls, which have receded northward a little over 8 miles, is estimated to be 12,000 to 16,000 years.

Evidence from Seasonally Banded Clay Deposits.—Another method of time measurement that is accurate as regards at least considerable portions of late Wisconsin and postglacial time is by the study of the seasonally banded layers (*varves*) of clay or fine silt deposited in temporary glacial lakes. A varve consists of two layers, a thick and a thin one. The thicker, slightly coarser, and generally lighter-colored layers represent the more rapid deposition in the summer period when the melting of ice was greatest, whereas the thinner, finer, and darker-colored deposits represent the winter season. Count of the pairs of bands in any one deposit gives a measure of the years represented in making the deposit, while careful measurement of the thickness of the successive bands affords basis for correlation of the banded deposits of different lakes and areas. The record may be thus pieced together to give a fairly continuous time

record. Study of these banded clays in New England and eastern Canada indicates that the retreat of the ice in this region required 28,000 to 29,000 years (Antevs). Although the measurement of time actually represented by the varves may be accurate, estimates from varve studies of the entire time since the maximum Wisconsin invasion are of doubtful value. They indicate, however, that the time involved is long. The consensus of judgment is that postglacial time (that is, since the beginning of retreat of the late Wisconsin ice) is of the order of 25,000 years.

Estimate of Duration of Quaternary Time.—If we accept 25,000 years as the best determination of the duration of time since the beginning of recession of the late Wisconsin ice sheet, the values for preceding interglacial ages as indicated by the comparative figures previously given are: Aftonian 200,000 years, Yarmouth 300,000 years, and Sangamon 120,000 years. Post-Iowan time is 55,000 years.

Estimate of the duration of times of glaciation may be determined roughly by figuring the time required for the advance and retreat of the ice sheet as determined by the average rate for the Wisconsin ice. Several thousands of years were certainly required for the growth of the continental glacier to such size that places 1,500 miles from the centers of radiation were covered by the ice sheet. Additional thousands of years were undoubtedly required for the retreat of the ice. The thickness of the glacial deposits of the different drift sheets does not furnish a satisfactory basis for estimates of possibly varying duration of maximum ice spread. A minimum figure for each glacial age seems to be 20,000 years. It is very certain that the times of glaciation, even though 30,000 to 50,000 years in length, were extremely short as compared with the duration of the interglacial ages. If we take the figures given above, it is concluded that the Quaternary period can hardly measure less than 750,000 years. According to the opinion of some, it may be as much as 3,000,000 years.

Causes of Glacial Climate

There is as yet no wholly satisfactory explanation of glacial climate. It is true that, wherever there is a cumulative annual surplus of snow over loss by melting and evaporation, glaciation will ultimately ensue. It is also true that glacial ice is now formed at high altitudes and high latitudes where the requisite precipitation and cold are present. From a geological standpoint, however, any hypothesis of the causes of glacial climate not only must include occurrence of these conditions which lead to glaciation on a scale far exceeding the present but must also account for their recurrences. Further, we desire to know why Pleistocene glaciation was centered in North America and northwestern Europe with very little effect in Asia or in the Southern Hemisphere; also why glacial climates have been distributed in the earlier parts of geologic history as

they have been. The Permian glaciation appears to have been even more severe than that of the Pleistocene. It affected Brazil, South Africa, India, and Australia, locally reaching to within 18 degrees of the Equator, while at that time North America and Europe were almost or entirely unglaciated. The problem, therefore, includes the recurrence of glacial conditions at different times in earth history and affecting different parts of the globe.

Factors Controlling Glaciation.—Since temperature and precipitation are the two factors involved in producing glaciation, we may consider the possible causes that control them.

Atmospheric *temperature* on the earth is due to the heat from the sun and radiation from the earth, the latter including heat derived both from the sun and from the interior of the earth. Measurement of solar radiation shows that there is a variation in output of heat energy amounting to 5 or 10 per cent for periods of a few days, and that there are smaller variations in long periods that are perhaps related to cycles of sun-spot activity. Radiation or reflection of heat from the earth varies mainly with the angle of incidence of the sun's rays. Heat derived from the interior of the earth is unimportant and there is no basis for inferring significant geographic or periodic variation. Finally, the amount of dust particles and molecules of carbon dioxide and water vapor in the atmosphere greatly influences temperature. Atmospheric dust absorbs, radiates, and reflects the sun's rays, causing lower temperatures at the earth's surface. Large quantities of atmospheric moisture and carbon dioxide retard radiation of heat from the earth and have, therefore, a warming effect. In general, high altitudes and high latitudes mean cold, and low altitudes and low latitudes mean warmth.

Precipitation is controlled by the amount of water vapor in the air and the air temperature. Since warm air has a high moisture capacity and cool air a low one, the lowering of air temperature favors precipitation. Wind movements, especially upward currents such as occur along mountain ranges, tend to produce rain- or snowfall.

Thus, the chief possible variables which go to make a glacial climate appear to be (1) total heat received from the sun, (2) latitude, (3) altitude, (4) atmospheric constituents, (5) precipitation, and (6) geographic factors controlling air temperature and precipitation. Each of these factors, as well as the climatic theories based on them, will be discussed briefly.

Variation in Solar Energy.—If variation in the amount of energy radiated from the sun is primarily responsible for the Pleistocene and other glaciations, then the cause of the distribution in time of these variations is unexplained. Furthermore, it has been pointed out that all of the known glaciations have occurred at times of enlarged lands and restricted seas and to some extent near times of prominent mountain-building. Such coincidence is hardly fortuitous.

The heat received from the sun varies with distance at different points in the earth's orbit, and, because of slight annual shift in the position of the orbit's major axis, there is a periodic change in the orientation of the earth's polar axis at points of farthest recession from the sun. The period of the change is about 120,000 years. Reduction in the effect of solar heat from this cause has been urged as an explanation of glacial climates (Croll), the north and south polar regions being alternately subjected to refrigeration. Objection to this and other suggested astronomic causes of glaciation is found in the distribution of the geologically recorded glaciations in time and in their evident relation to emergent continental conditions. Solar variation is a possible factor in producing glaciation, but it is of uncertain validity and can hardly be considered the major cause of glacial climate.

Variation of Latitude.—Because of the slight effectiveness of the sun's heating in polar latitudes, these regions are cold and partly ice-covered. Consequently, in order to explain past glaciation in lower latitudes, hypotheses have been put forward suggesting that a possible shift of the earth's axis involving changes of latitude would naturally cause transfer of the ice caps to regions that had formerly been some distance nearer the Equator. Whether this assumption contemplates bodily change of axis of a rigid, solid earth or a lateral movement of the earth's outer crust (Wegener's hypothesis of wandering, "floating" continents), insuperable mechanical difficulties appear. Also, there are many details in which this assumed variation of latitude fails to satisfy geographic requirements. It seems preposterous as an explanation of the several glacial and interglacial ages of the Pleistocene.

Variation of Altitude.—Since cold increases with height above sea level, it is easy to account for existence of snow and ice at high altitudes even at the Equator, as on Mount Kilimanjaro in Africa. If northern North America and northwestern Europe were bodily elevated so that average annual temperatures were reduced to a point where rate of snow accumulation appreciably exceeded loss by melting, glaciation would result. Deep-cut fiords on the Scandinavian coast and occurrence of submerged stream valleys on the continental shelf on both sides of the Atlantic have been cited as evidences of former much higher elevation of the lands. If it is granted, however, that the glaciated areas were thus elevated, such elevation is a very doubtful main cause of glaciation. Reliable evidence points to upwarping of the land during the warm, interglacial times and a depressed condition due to the enormous weight of the ice during glacial times.

Variation of Atmospheric Constituents.—Since the thermal conductivity of the atmosphere is largely controlled by its content of dust particles, carbon dioxide, and water vapor, variation in the amount of these constituents has been appealed to as a major factor in causing glaciation.

Volcanic dust particles, which after explosive eruptions may float in the air for months or even years, act as a screen that prevents a part of the solar heat from reaching the earth. Temperatures at the earth's surface may be lowered several degrees, as was the case in the "years without a summer" following the explosion of Krakatoa in 1883. If the presence of atmospheric dust is an important factor in the initiation of glacial climates, times of extensive glaciation should be correlated with epochs of unusual volcanic activity. The geologic record contains evidence of several such times of tremendous vulcanism, but in most of these there is no indication of associated glacial climate. Nor do we find marks of especially great eruptive activity connected with the known times of extensive glaciation. It is possible, nevertheless, that, if other factors are favorable, the cooling due to eruptions of volcanic dust may cause initial accumulations of snow and ice, and when once started the cooling effect of the ice mass on surrounding territory favors increased precipitation of snow that may lead to formation of a glacial ice sheet.

Carbon dioxide is a warming, blanketing agent. Huge volumes of carbon dioxide are locked up in limestone and coal. If the amount of carbon dioxide used in making extensive sedimentary deposits of these kinds greatly exceeds additions of this gas to the atmosphere from volcanoes, from effects of erosion, and through the agency of organisms, the blanketing effect is reduced, and, according to arguments, glaciation may result. Permian glaciation followed the great coal-making period of the Carboniferous, when also extensive limestone deposits were formed. On the other hand, there was neither very much coal nor limestone in the Tertiary period preceding Pleistocene glaciation. Further, although much limestone and coal were formed in the Cretaceous period, the formation of great mountain chains and the elevation of continents which occurred toward the end of the Mesozoic were not accompanied by continental glaciation.

Atmospheric water vapor is a much more important climatic factor than carbon dioxide. Variation in the quantity of water vapor in place and time is controlled primarily by geographic conditions. Since the latter are constantly modified by geologic agencies, conditions of atmospheric moisture, favorable or unfavorable to glaciation, may be expected to change with geologic time.

Variation of Precipitation.—Low mean temperature unaccompanied by at least moderate precipitation cannot produce glaciation. Most of Siberia has a mean annual temperature below freezing, but the yearly total rainfall is less than 20 inches and it is under 10 inches over a very large territory. Consequently, there are no permanent snow or ice fields. If precipitation were sufficiently increased, it is certain that under present conditions an ice sheet would be formed in Siberia. Evidently variation of precipitation, together with other factors, may be a cause of glacial climates. But there are several reasons for the belief that this cannot be the sole cause of the Pleistocene glaciations.

Geographic Variation.—There is almost universal variation of actual temperatures at points on the earth's surface, and what may be considered "normal" for corresponding latitudes and altitudes. For example, a point in Scandinavia at 70° North latitude has a higher mean temperature than one at 50° on the east coast of North America, and the Scandinavian point designated is about 30 degrees warmer than a corresponding latitude in eastern North America. This difference is largely due to the influence of the Gulf Stream. Oceanic currents, distribution of sea and land, the direction, moisture content, and other characters of the prevailing winds, and topography are about as important climatic factors as latitude and altitude. A majority of these factors are complexly interrelated. It seems evident that geographic changes that modify oceanic and atmospheric circulation may have far-reaching climatic results. A combination of conditions favoring sufficiently low summer temperature and moderately high precipitation necessarily means glaciation. That this combination of conditions has recurred in various parts of the world at different times in earth history is intrinsically no more surprising nor presumably more difficult to explain than the recurrence at various places and different times of desert climates. Because the formation of ice is controlled by a definite temperature, and because (owing to absorption of latent heat, high efficiency in reflecting the sun's heat, and other characters) the establishment of a snow or ice field has a cumulative effect on further growth, change in climate that passes beyond a certain critical point has a trigger effect that leads to sudden culmination of glacier-making tendencies.

Gradual change of atmospheric and marine circulation, with accompanying modification of temperature and precipitation, which very possibly may result from glaciation itself, may at length reverse the process, introducing a long, warm nonglacial age which is geologically the normal earth climate. This in turn, by changes similar to those that inaugurated the glacial cycle, may cause a swing of the climatic pendulum in the opposite direction. The Pleistocene, Permian, and to a lesser extent the other known glacial epochs show clearly these alternating cycles, which are not necessarily of the same time value. As previously noted, glacial climates are unknown in parts of earth history when the seas widely transgressed the continents; they occur rather at times when lands were enlarged and when important mountain ranges existed. Not all enlarged lands or prominent mountain ranges have been accompanied by glaciation on a large scale, but seemingly the control of temperature and precipitation by geographic conditions is a large, if not the controlling, factor in the appearance and disappearance of continental ice sheets.

Conclusions.—Glaciation is due to a combination of low temperature and moderately high precipitation. Probably the most important factors controlling these are of geographic origin, including especially

circulation of the atmosphere and oceans and the existence and location of mountain barriers. Contributing factors may possibly be the variation in atmospheric constituents and solar radiation. Distribution of the major glacial epochs in geologic time and their location geographically are related to diastrophic movements that produced mountains, changed the outline of continents, and affected atmospheric and oceanic circulation. Rhythmic alternation of glacial and nonglacial ages within the glacial epochs may be interpreted tentatively as the result of reversed oscillations primarily controlled by atmospheric and oceanic circulation. No adequate cause of variation in sun energy, atmospheric constitution, or vertical movement of the land coincident with this periodicity of glaciation is known.

SUMMARY

The Quaternary period includes the time from the beginning of glaciation in the latter part of the Cenozoic era to the present. This period includes the Pleistocene epoch, which contains several glacial and interglacial ages and comprises more than 95 per cent of the period, and the Recent epoch, which includes the time since the retreat of the last continental ice sheet.

The chief feature in the physical history of Quaternary time is extensive glaciation. The northern part of North America and northwestern Europe were glaciated, and smaller ice sheets and numerous large mountain glaciers were present in other regions. At least four times during the Pleistocene epoch, great ice sheets made appearance and then vanished. The interglacial ages were very much longer than the glacial. Differentiation of the deposits of the successive glaciations and approximate measurement of their relative age are established by observations of weathering effects on the drift sheets, especially depth of leaching of calcareous materials and the formation of gumbotil.

In North America the first (Nebraskan) and second (Kansan) glaciations extended southward from the region west of Hudson Bay (Keewatin center) to the position of the lower Missouri River; and from regions in Labrador (Labradorian center) to New Jersey and Pennsylvania (Jerseyan drift). The third glaciation (Illinoian) affected territory southwest of the Labradorian center as far as Illinois and also south to Ohio, Pennsylvania, and southern New England; western equivalents are not definitely known. The fourth glaciation (Wisconsin) may be considered as consisting of four subordinate ice advances: (1) Iowan, which is definitely known only in Iowa and adjacent country to the north and northwest, (2) Tazewell, which is represented by widespread drift in Illinois, Indiana, and Ohio, (3) Cary, which is recorded by drift in the regions bordering the Great Lakes on the south and west, and (4) Mankato, which produced the drift that covers western Minnesota, the eastern

Dakotas, and most of the northern part of the continent. The earlier ice sheets appear generally to have covered a larger total area than the later, for the older deposits extend farthest from the centers of ice radiation; restricted exposure of the older drifts is due partly to covering and partly to removal by later glaciations.

The Great Lakes were formed during the retreat of the Wisconsin ice sheet by ponding of water in large depressions formed partly by stream erosion, partly by glacial erosion and deposition, and partly by deformation of the land. Several stages in the development of the lakes are marked by beaches above the present lake levels and by other physiographic evidence. The early stages of the lakes were controlled by the ice front on one side and the position of the lowest available outlet on the other. Southwestward tilting of the land influenced some of the changes of the lakes.

Mountain glaciation was most extensive at the times of advance of the continental ice sheets. Early Pleistocene deposits of mountain glaciers are found at high levels on remnants of ancient piedmont terraces, beneath which subsequent erosion has carved valleys hundreds of feet deep. Intermediate and late Pleistocene glacial deposits are found in these valleys.

Nonglacial deposits of Quaternary age consist of marine sediments, wind-carried dust and sand, alluvium of streams, and sheet wash, lake beds, swamp muck, spring and cave deposits, and lesser materials. At different levels along the Atlantic and Gulf Coasts are marine terraces which occur to more than 250 feet above present sea level and on which are thin marine deposits. These terraces, which record higher relative positions of the sea, are possibly to be correlated with interglacial ages when the water of the ice sheets was returned to the sea.

Results of stream work are on the whole most important in the Quaternary record of the nonglaciated parts of the continent. Numerous readjustments of drainage, as in the formation of the present Ohio and Missouri Rivers, are indicated in the country near the ice edge. The alluvial plain and delta of the Mississippi were greatly extended during this period. Widespread deposits of calcium carbonate-cemented sand and gravel on the High Plains were deposited partly during Quaternary time.

The sculpture of the Rocky Mountains and other ranges of western North America, and of the Colorado Plateau region, is due mainly to stream erosion of the Quaternary period. A great thickness of alluvial deposits and, in places, of lake beds occurs in the depressions between the mountains of the Great Basin. Very large lakes (Bonneville, Lahontan) came into existence at this time but have since almost disappeared through desiccation. The Columbia River region bears evidence of extraordinary erosion and deposition of ice-flood waters.

The Pacific Border has been unstable throughout Quaternary time, as shown by folding and faulting of Quaternary marine and nonmarine sediments, as well as by frequent earthquakes in Recent time.

Volcanic activity is recorded in western North America by sheets of lava and cinder cones, many of which are very recent in appearance.

The Quaternary record of other continents is comparable with that of North America. There were four glaciations in Europe, with continental ice sheets in the north and greatly enlarged mountain glaciers in the Alps and other mountains. Asia and, in lesser degree, other continents show presence of glaciation in places. In addition, other kinds of Quaternary deposits and the effects of erosion are very important.

The Quaternary period has a duration of at least 750,000 years and probably more than a million years.

The cause of glacial climates is a complex problem. Probably no one factor is alone responsible but the association of glaciation and times of prominent mountain development and continental protrusion is significant. Geographic factors including distribution and size of land masses, location and elevation of mountains, and attendant effects of these features on atmospheric and oceanic circulation are believed to have a controlling influence.

CHAPTER XXIX

LIFE OF CENOZOIC TIME

Just as the record of the earth's physical history in Recent geologic time is more clearly and completely written, so the changing character of life on land and in the sea during the Cenozoic era is better known, in general, than in the ancient geologic periods. This life of Cenozoic time is particularly interesting because we find here the immediate ancestors and also the progressively more remote antecedents of the animals and plants of the present day. The evolution of many groups of organisms can be traced step by step from primitive generalized forms to varied, often highly specialized modern species. There are also numerous lines of development that during Cenozoic time have ended in extinction. The record of several branches, one of which (the Primates) includes the monkeys, apes, and man, is fragmentary. Altogether, however, a fairly clear picture can be drawn of the life of the successive Tertiary epochs and of the Quaternary period.

The outstanding animal group of Cenozoic time is that of the mammals, which are the highest type of living creatures. We shall, therefore, give first attention to the mammals and outline the main features in their remarkable expansion, differentiation, and rise to dominance on the earth. The prominence of flowering plants is the main characteristic of Cenozoic time in the plant world.

CENOZOIC ANIMAL LIFE—THE AGE OF MAMMALS

Mammals

The Cenozoic era is preeminently the "Age of Mammals," for these most highly organized of the vertebrate line not only underwent a remarkable series of evolutional changes leading from simple and generalized to highly specialized creatures but in variety and numbers quite took the place vacated by the reptilian lords of Mesozoic time.

This great advance is especially important to us, perhaps, because we ourselves are mammals. Also, we find in the Tertiary rocks the beginning or early stages of most of our familiar modern domestic and wild animals. On the whole, the fossil record is nearly all that could be asked for. Fossil mammals are abundant at many horizons and localities, and in most cases the bones are very well preserved. There are several thousands of more or less well-known fossil species of mammals.

This must not be understood to mean that knowledge is anywhere nearly complete, however. On the contrary, as is true in almost all branches of paleontology, there is surely much more that is unknown than known. A few groups of mammals, such as the horses, are fairly well represented by described species that show each stage in evolution from near the beginning to the present time and that show also the branching of various offshoots. But even here the record is deficient at the beginning and there are probably intermediate stages and branches of the horse family as yet undiscovered. Most of the mammalian groups are much less completely known.

The history of the mammals shows a beginning that dates back at least to Triassic time; a slow almost negligible development in the Mesozoic era; a sudden acceleration of evolutional change in the oldest Tertiary, leading in the Eocene to increase in average size, larger mental capacity, and special adaptations for different modes of life; further improvement and radiation in the Oligocene, with appearance of some new lines and extinction of others; and in the Miocene and Pliocene, culmination of several groups with continued approach toward modern characters. The history is far from ended. The peak of the career of mammals in variety and size is generally regarded as having been attained in Miocene times. The larger mammals of the present day are a dwindling remnant of groups for which the end is almost in sight. The branch of the mammals represented by man, is, however, the ruling animal of the modern world.

Radiation and Adaptation of Mammals.—The radiation and adaptation of mammals to almost all possible modes of life parallel those of the reptiles in Mesozoic time. Except for greater intelligence, the mammals do not appear to have the advantage; that is, they are not more perfectly adapted in most cases than corresponding reptilian forms. The bat is probably no better as a flying animal than the pterosaur, and the dolphin is about as fishlike as the ichthyosaur. However, many of the swift-running mammals of the plains, like the horse and the antelope, must excel any of the dinosaurs or lizards. The tyrannosaur was a more ponderous and powerful carnivore than any flesh-eating mammal, but the lion or tiger is probably a more efficient and dangerous beast of prey because of a superior brain. But our purpose here is not so much to make comparisons as to point out that different branches of the mammals have gradually fitted themselves for all sorts of life on the lands, grazing on the plains and able to run swiftly (horses, deer, bison), living in rivers and swamps (hippopotamus, beaver), dwelling in trees (sloth, monkey), digging underground (mole, rodents), feeding on flesh in the forest (tiger) and plain (wolf), swimming in the sea (dolphin, whale, seal), and flying in the air (bat). Man is becoming able by mechanical means to conquer the physical world and to adapt himself to almost any set of conditions.

This radiation and adaptation are responsible for gradual changes of form and structure. It is biologically characteristic and only possible in the youthful, plastic stage of a group or, to a degree, of an individual. At an early stage in its career a phylum or class or family or genus seems to possess a capacity for change which, as the unit becomes old and fixed, disappears. The simple, generalized types retain longest and best this

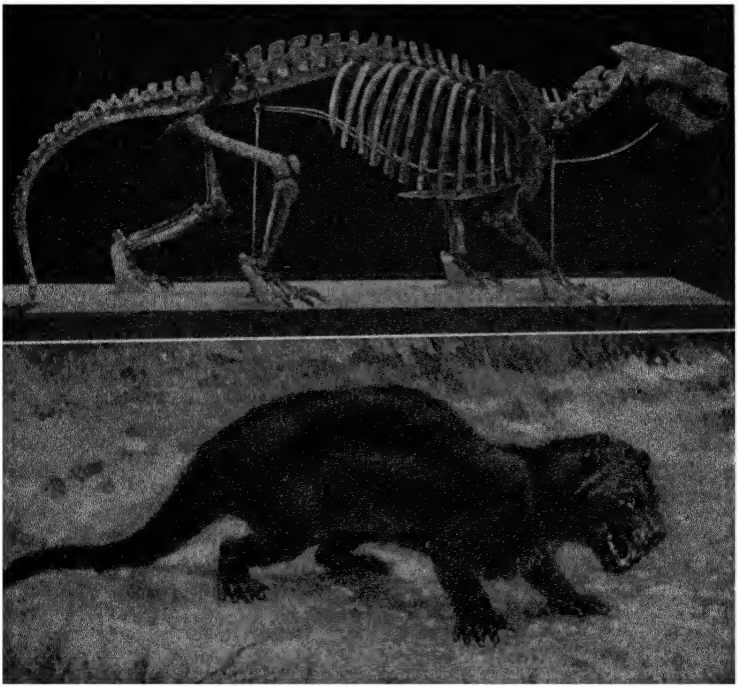

FIG. 364.—One of the early types of carnivorous mammals called creodonts, *Patriofelis*, from the Eocene beds of Wyoming. (*American Museum of Natural History*.)

ability to "carry on" and to make adjustments when required. Probably it is from them that the progenitors of new, fecund stocks take origin—certainly not from any of the specialized end products. So, in the mammals we witness again the birth, plastic radiation in many directions, increasing specialization, and in some branches the extinction, which we have learned from observation of the geologic record of life is a characteristic of the evolution of life.

Characteristics of the Mammals.—The mammals are distinguished from other animals chiefly by the possession of milk glands (*mammae*, from Latin meaning breasts) which serve to suckle the young, and by having a more or less complete body covering of hair, which is as dis-

tinctive of the mammals as feathers are of birds. Like birds, the mammals are warm-blooded and have a four-chambered heart. Unlike other vertebrates, the body cavity is divided by a diaphragm into a thoracic region, which contains the heart and lungs, and an abdominal region, which contains the stomach, intestines, and accessory organs. The brain is relatively large and in some classes, such as the Primates, it is intricately convoluted, the seat of high intelligence. In all but the very lowest types the young are born alive, but to varying degree they are dependent for a time on parental care.

The skeleton and teeth of the mammals, on which knowledge of fossil species almost exclusively rests, are fundamentally little different from those of reptiles. There is the same structural plan consisting of skull, vertebral column, ribs, shoulder and pelvic girdles, four limbs with one upper and two lower bones, wrist and ankle composed of small bones, and digits that primitively number five on hand and foot. This skeleton is a reptilian inheritance. It is true that there are certain differences in the structure of the skull of the mammal and reptile, but these are evidently due to modification and specialization of the mammals. Some of the archaic mammals approach the reptiles so closely that the distinguishing details are altogether trivial. The teeth of the mammals are highly varied in form, depending mainly on function, and they differ from the common type of reptilian teeth. Differentiation of the teeth into incisors, canines, premolars, and molars is a typical mammalian character (seen also in theriodont reptiles, from which mammals were probably derived). Commonly there are two sets of teeth, the milk dentition which is lost in youth, and the permanent dentition which grows in later. As in the case of the variously modified reptiles of Mesozoic time, the life habits of mammals are reflected in characters of the teeth and skeleton. This fact and comparison with related living mammals make possible fairly accurate determination of the habits of extinct species. Even the appearance of these animals in life, generally excepting such features as color, may be reconstructed. Several such restorations, based on much careful scientific study, are given in this chapter.

Origin and Classification.—On the basis of known Mesozoic fossil mammals and the discovery of mammal-like characters in certain of the Permian reptiles, the beginning of the mammalian line may be assigned to a time near the close of the Paleozoic era, and the ancestral stock was undoubtedly a small, active reptile belonging probably to the theriodont or cynodont group. Most important in the change to characters of the mammal was the gradual introduction of warm blood. This may have distinguished some of the reptiles and it was developed in the birds, also of reptilian origin. The body temperature of lowest mammals is variable.

The most primitive mammals (duck-billed mole and spiny anteater of Australia) are hatched from eggs, like almost all reptiles. These are set apart in a subclass (Prototheria) to which the majority of Mesozoic mammals belong. The vast remaining group of mammals is likewise divided into two very unequal parts: (1) the pouched mammals, in which the young are born alive but so immature that the protection of the pouch is required in earliest life (opossums, kangaroos), and (2) the placental mammals, in which the young are much more fully developed before birth. To this last group practically all common mammals belong and, in addition, several extinct orders.

Fossilization of Mammals.—Remains of mammals are found in many kinds of deposits, stream-laid clays, sands, and gravels, lake

FIG. 365.—*Tetrabelodon*, four-tusked Miocene elephants of the western North American plains. (*C. R. Knight, Field Museum of Natural History.*)

and swamp beds, wind-blown dust and sand, volcanic ash, asphalt, cave earth, marine sediments (mostly marine mammals), and less commonly still other materials. The kinds of mammals, numbers, and state of preservation depend on the nature of the deposit, its geologic age, and other things. It is worth while to observe a few of these fossil beds and consider their origin.

The great majority of Tertiary mammal fossils occur in sediments of ancient valleys and plains; they indicate burial in streams or boggy or quicksand areas along stream courses, in shallow lakes or swamps, and occasionally in wind deposits. In each of these cases it is easy to imagine how numbers of animals might be caught and buried, for such capture and burial are not infrequently observed in modern time. Especially in periods of drouth, starved and drink-crazed animals seek watering places in large numbers and, very much weakened, are unable to escape from clinging mud. Or, in exhausted condition, they drink to excess, and, especially if the water is strongly mineralized, this is almost immediately fatal.

In a hard year on the western ranges one may see many carcasses of cattle dead from this cause and from thirst. Darwin describes a long drouth in Argentina in 1827–1832 when cattle in herds of thousands rushed into the Parana River and, being exhausted by hunger, were unable to crawl up the muddy banks and thus drowned.

The arm of the river which runs by San Pedro was so full of putrid carcasses that the master of a vessel told me that the smell rendered it quite impassable. Without doubt several hundred thousand animals thus perished in the river. . . . All the small rivers became highly saline and this caused the death of vast numbers in particular spots. Azara describes the fury of wild horses on a similar occasion rushing into the marshes, those which arrived first being overwhelmed and crushed by those which followed. . . . He has seen upwards of a thousand wild horses thus destroyed. . . . Subsequent to the drouth of 1827 to 1832 a very rainy season followed, which caused great floods. Hence it is almost certain that some thousands of the skeletons were buried by the deposits of the very next year. (Darwin.)

In arid regions, animals may suffocate in dust storms or die from thirst and the skeletons are buried readily in wind-blown sand. In northwestern Kansas, Williston found nine skeletons of a species of large wild hog lying huddled together with their heads all pointing in the same direction, and Gidley in South Dakota discovered six skeletons of three-toed horses crowded together, probably killed and buried by a sand storm.

It is generally found in collecting fossil mammals that they are not evenly distributed through the beds but occur rather in "pockets," with numbers of individuals crowded together. And some layers contain numerous fossils, while others are entirely barren. Some of the reasons for these irregularities and the causes of burial are evident.

One of the most interesting occurrences of fossil mammals in the western United States is the Rancho La Brea asphalt deposits near Los Angeles. The asphalt has been formed by the oxidation and solidification of petroleum that seeps upward through Pleistocene deposits from oil-bearing strata below. In the change from petroleum to asphalt, very viscous, sticky tar pools have been and are formed on the surface of the ground. These pools entrapped a multitude of Pleistocene mammals and birds, sealing their bones perfectly from decay. Merriam observes concerning present-day conditions that animals "are very quickly rendered helpless by the gummy mass, which binds their feet and in their struggles soon reaches every part of the body." The skeletons in this deposit include a preponderance of carnivorous mammals and birds, which is very unusual, for the carnivores are rarely found in numbers.

Whenever an animal of any kind is caught in the tar, its struggles and cries naturally attract the attention of carnivorous mammals and birds in the immediate

vicinity, and the trapped creature acts as a most efficient lure to bring these predaceous animals into the soft tar with it. It is not improbable that a single small bird or mammal struggling in the tar might be the means of entrapping several carnivores, which in turn would serve to attract still others. . . . In the first excavations carried on by the University of California a bed of bones was encountered in which the number of sabertooth (cat) and wolf skulls together averaged 20 per cubic yard (Merriam).

FIG. 366.—Restoration of the saber-toothed tiger *Smilodon*. Abundant remains of this ferocious, highly specialized member of the cat family have been gathered from Pleistocene asphalt deposits near Los Angeles, Calif. (*C. R. Knight, American Museum of Natural History.*)

Occurrence of Fossil Mammals.—The land deposits of Cenozoic age in many parts of the world, but especially in the western part of the United States, have yielded a wonderful series of fossil mammals that not only shows the stages of development of various existing families but brings to light a host of offshoots from the mammal line that flourished for a time and then disappeared.

The Cenozoic record begins with earliest Eocene (Paleocene) beds, the chief fossil localities being located in northwestern New Mexico (Puerco and Torrejon beds) and in parts of Wyoming and Montana (Fort Union). The chief fossil horizons in the lower Eocene, however, are in slightly higher beds (Wasatch) and are widely distributed in central and southern Wyoming, Utah, and New Mexico. In the top part of the lower Eocene in central Wyoming are other but less abundant fossils (Wind River). The middle Eocene of Wyoming (Bridger) has yielded a variety of interesting mammals, and in the upper Eocene are still other fossil-bearing deposits (Uinta) chiefly worked in northeastern Utah.

There are two chief regions of Oligocene mammals. The early and middle parts of the epoch are represented by the famous White River beds in the badlands region of southwestern South Dakota and adjacent parts of Nebraska and Wyoming. Three distinct zones are present here and three-quarters of a century of collecting has yielded a larger number of complete fossil mammal skeletons than is known from any other like area in the world. The strange mammals of this early day are therefore relatively well-known. The other Oligocene fossil collecting ground is the John Day Basin in eastern Oregon; it represents a slightly later fauna.

Miocene bone beds are widespread in the Great Plains country from South Dakota to Kansas and Colorado, and in central Wyoming (Arikaree). The number and variety of the fossils are very great.

The best Pliocene mammal localities are also found in the plains deposits east of the Rockies, especially in western Nebraska, Kansas (Ogallala), and northwestern Texas.

Pleistocene mammals have been found in practically all parts of the continent, in stream deposits, swamps, caves, and near Los Angeles in the asphalt deposits described.

South America, chiefly in the Argentine, has yielded a remarkable assemblage of fossil mammals differing almost wholly in character from that in the northern continent. The Old World contains fossil mammals in many places, especially in France, southeastern England, Switzerland, southern Germany, and Italy. Eocene deposits near Paris are famous because of the classic studies of the great naturalist Cuvier. Asia is less explored than Europe, but fossil mammals are known in Tertiary deposits of the Himalayan belt, in China, India, Japan, and elsewhere. Recent expeditions of the American Museum of Natural History into the Gobi Desert of Mongolia have been successful in unearthing numerous interesting fossil mammals, including *Baluchitherium*, the largest land mammal known.

Evolution of the Chief Orders of Mammals

We shall now observe the characteristics of a few of the mammal orders at various stages in their development as shown by fossil remains.

ARCHAIC HOOFED MAMMALS

The Early Tertiary formations contain two main groups of primitive hoofed mammals which are partly ancestral to the varied host of later hoofed animals (ungulates) but which are certainly in part unsuccessful offshoots. They are the condylarths ("knuckle-jointed"), and the amblypods ("blunt-footed"), both restricted to the Eocene.

Condylarths are exceedingly primitive hoofed creatures with five digits on each foot, a generalized type of body, and a long heavy tail,

resembling in many ways some of the early clawed mammals. The skull is long and low, the brain case small, and the teeth unspecialized and low-crowned. The best-known genus (*Phenacodus*) had about the size of a small shepherd dog. The condylarths approach the characters of the hypothetical ancestors of the ungulates, but the fossils so far discovered can hardly be in the direct line of descent of these. They are nore closely related to the odd-toed than to the even-toed hoofed mammals. The group disappeared before Medial Eocene time.

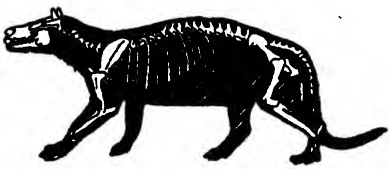

Fig. 367.—*Phenacodus*, best-known genus of the primitive hoofed animals called condylarths. Eocene, western United States.

Amblypods are distinguished by stout, pillar-like limbs ending in short, blunt feet like those of an elephant, and by the archaic nature of the teeth and skull. The brain capacity was small. These animals, which are one of the most prominent groups of Eocene time, show a gradual increase of size and an interesting specialization of the skull. The oldest (*Pantolambda*, Paleocene) had a narrow head and long body somewhat smaller than those of a sheep and much shorter legs; the tail was long and catlike. The general form of the animal suggests its cousins, the condylarths. In the lower Eocene Wasatch beds the most

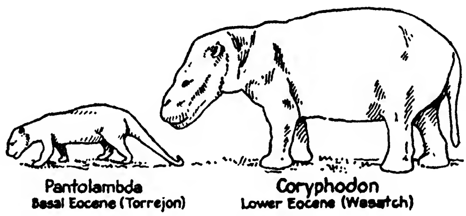

Fig. 368.—The oldest, most primitive known amblypod *Pantolambda*, and a later, more advanced member of this group, *Coryphodon*. Eocene, western United States.

common mammal is *Coryphodon*, a heavy, sluggish amblypod with broad flattish skull that bore no horns but carried on the upper jaws a pair of swinelike tusks. This animal attained the size of a cow. The culmination of the amblypods is seen in the middle Eocene Bridger beds, where they are the most striking and characteristic mammals. There are several kinds, but all are commonly called uintatheres, after the best-known genus (*Uintatherium*). In appearance and bulk, the body of these creatures resembled a small elephant with a height of about 7 feet, but the head was most unlike an elephant. The long nasal bones indicate that there was no trunk, for development of a trunk is always accompanied by shortening of these bones. The top of the long skull carried three pairs of horns, the front pair above the nose possibly sheathed with horn as in the rhinoceros, the middle pair

above the eyes and the back pair at the base of the skull being rounded at the ends and probably covered with skin as in the giraffe. The top of the back part of the skull is peculiarly depressed and dish-shaped,

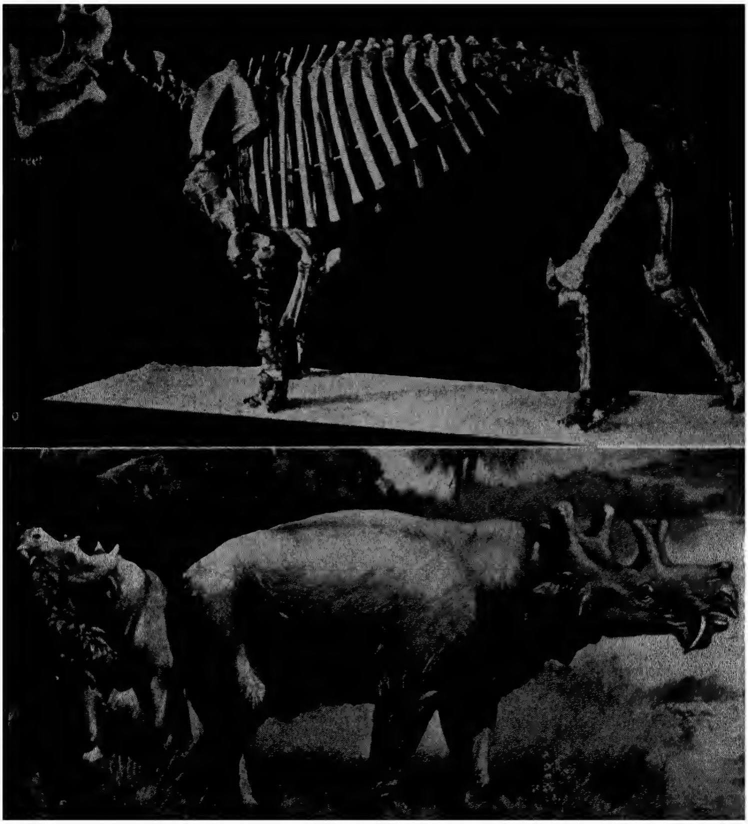

Fig. 369.—Skeleton and restoration of the amblypod *Uintatherium*, from the late Eocene deposits of Utah. (*American Museum of Natural History.*)

leaving little space for the brain, which was indeed small. The males carried long curved or spearlike tusks projecting downward from the upper jaws. The uintatheres were assuredly bizarre-looking animals. They are the last of the amblypods, disappearing in the late Eocene (Uinta).

THE ODD-TOED HOOFED MAMMALS

The two largest divisions or orders of hoofed mammals are differentiated on the basis of foot structure, the so-called odd-toed group (perissodactyls), in which the central toe is larger than the others because it bears more of the weight, and the even-toed group (artiodactyls),

in which the weight is borne mainly or wholly on two toes of the same size. The most important of the first group is the horse, man's comrade and most valued domestic animal. Other odd-toed hoofed mammals are the rhinoceroses, tapirs, and the very strange extinct animals called titanotheres and chalicotheres.

Horses.—The horse is a highly and efficiently specialized mammal, distinguished chiefly by characters of the limbs and teeth. The limbs are wonderfully fitted for running, which is the horse's chief means of

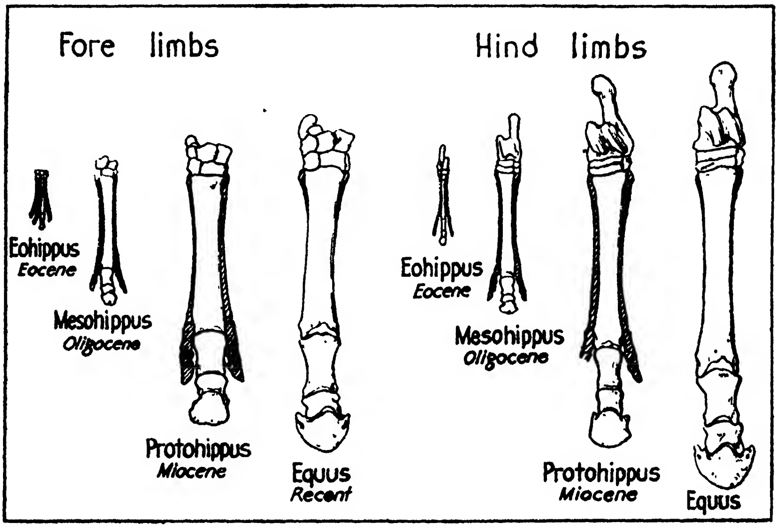

FIG. 370.—The lower part of the limbs of the modern and fossil horses, drawn to scale, showing progressive enlargement of the central digit and the gradual disappearance of the side toes. The part of the limbs represented is that below the wrist or ankle. (*Modified from Scott.*)

self-preservation. The teeth are specially adapted for grazing on the tough grasses of the plains. We shall examine first the character of these structures in the modern horse and then trace their development as shown by fossil species.

The limbs and feet of the horse differ from those of all other hoofed mammals in that there is but a single functional toe or digit on each limb. Comparison with other animals shows that the horse walks on the very tip of finger and toe; the wrist is the "knee," the ankle is the "hock," and the elbow and real knee are close up to the body. Thus, the long slender limb results essentially from lengthening of the lower bones, the upper ones carrying the powerful well-bunched muscles that propel the lower limbs by means of thin strong ligaments. Although the lower limb consists of a single digit, the bones are so increased in size that they form an adequate support. The joints are fitted with a tongue-and-groove arrangement so that only forward and backward motion is possible. Altogether the limb structure is so perfectly designed

for running swiftly that one may well doubt the possibility of further development along this line in an animal of the size of the horse.

The teeth consist of long-crowned cropping teeth (incisors) in front, very long-crowned grinding teeth (molars and premolars) behind, and in the males, but rarely in females, tusks or canines. The incisors are peculiar in having a deep pit in the cutting face of the tooth, which is due to an infolding of the hard enamel, like the pushed-in end of the finger of a glove. As the teeth are worn down, the size of the pit is reduced; this is used in determining a horse's age. The grinding teeth are nearly square in cross-section and the three elements of the tooth structure, enamel, dentine, and cement are elaborately infolded so as to give a characteristic pattern of the more resistant enamel upon the wearing surface. The teeth have an excessively long crown so that years of wear are compensated by gradual outward growth of the grinders. In extreme old age they are worn down near the roots. The premolars of the horse have assumed the characters of the molars. The long grinding teeth are accommodated in the skull by a deep lower jaw and by the elongation of the skull with the eye orbit well back, giving room for the teeth in the upper jaw.

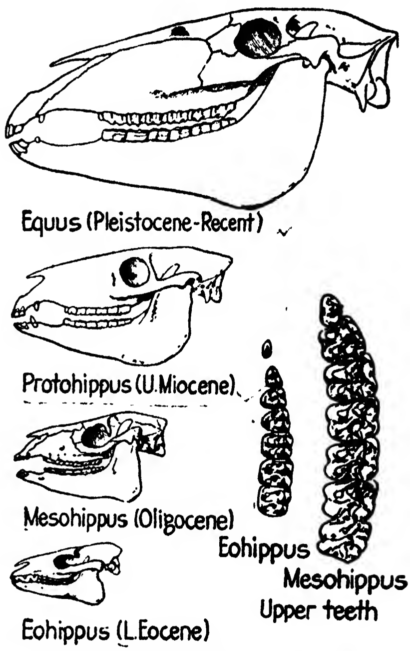

FIG. 371.—Evolution of the skull of the horse (left) and teeth of Eocene and Oligocene horses (right). (*After Scott.*)

Horses have attained a large size, exceeded only by a few other kinds of land mammals. Some of the draft horses reach a shoulder height of 6 feet 4 inches and a weight of 2,400 pounds. The horse is a very intelligent animal. The brain is not only large but is of a relatively high type, well convoluted. Like man and the elephant, the horse has shown the ability to adapt himself to all climatic environments. However, horses in the natural wild state are restricted to parts of Asia and Africa, all of the living horses of other continents, including the wild mustangs of western North America, having been introduced by man.

Evolution of Horses.—The oldest known horses are diminutive creatures, about a foot high, skeletons of which occur in lower Eocene deposits of North America (*Eohippus*, the "dawn horse," Wasatch beds) and southern England (*Hyracotherium*). These might really fail of recognition as primitive horses except for the almost complete series of

intergrading fossils in later Cenozoic rocks that definitely connect the dawn horse with living horses. The Old World type is a little more primitive than the American and may well have been ancestral to the rhinoceroses and tapirs as well as horses, for the generalized teeth and skeleton have characters common to all of these. *Eohippus*, about the same as a fox terrier in size, has limbs of moderate length, with four

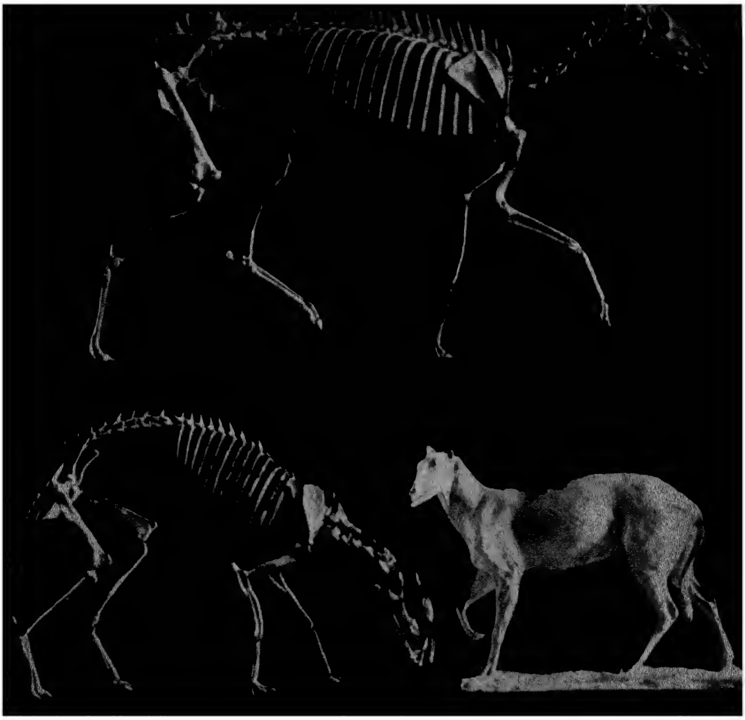

Fig. 372.—Skeleton and restoration of the Eocene "dawn horse" (*Eohippus*) below; skeleton of a three-toed Miocene horse (*Protohippus*) above. (*American Museum of Natural History.*)

complete toes on the forefoot, and three, with remnant of a fourth, on the hind foot. The two bones of the forearm and foreleg are both separate and normal. The animal was adapted for running but did not walk on the tips of the digits as later horses. The teeth are very unlike those of the modern horse in that the crown is short and the grinding surface consists of cusps that only begin to show the structure of the teeth in later types. The last premolar is becoming like the molars. These teeth were fitted for browsing rather than grazing and suggest, with other evidence, that the American dawn horse was a forest dweller, not a creature of the open plains.

The middle Eocene (Bridger) beds contain a slightly larger and less primitive fossil horse, and the upper Eocene (Uinta) another. Climatic changes in Oligocene and Miocene time, with decrease of forests and increase of meadow and plains country, are probably responsible for the chief modifications seen in the several genera of fossil horses from deposits belonging to these epochs. There is a distinct but gradual increase in size, the toes on each foot are reduced to three, and the teeth, especially in some, show a marked change toward the modern horse. The late Miocene and the Pliocene horses carry these modifications farther and we find here the first one-toed horse, the remnants of the side toes being represented merely by bony splints below the wrist and ankle. Contemporary horses, however, still retain small but complete side toes. There are offshoots of the horse stock which existed for a while and then died out. The Pleistocene deposits of North and

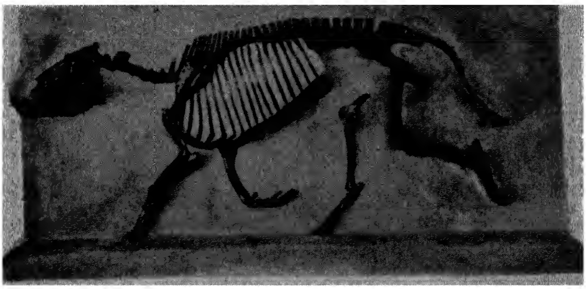

FIG. 373.—Skeleton of a small, swift-running rhinoceros (*Hyrachyus*) of Eocene age. (*Peabody Museum of Natural History, Yale University.*)

South America contain numerous remains of horses which are essentially modern, but, for reasons that are entirely unexplained, horses became extinct in the Western Hemisphere before the beginning of the present or Recent geologic epoch. If Old World species that are probably migrants or descendants of migrants from North America had not survived, we should know the horse only as we do the amblypod, from fossil bones.

The evolution of the horse, more completely shown by discovered fossils than probably any other mammal group, shows clearly (1) lengthening of the limbs, (2) change of foot posture from digits with much of the length to only the tip in contact with the ground, (3) reduction in the number of digits on each foot to one, (4) reduction of smaller bones (ulna and fibula) of the limbs, (5) modification and complication of the teeth from a type adapted for browsing to one adapted for grazing, (6) elongation of the skull and neck, and (7) marked increase in size.

Rhinoceroses.—The fossil record of rhinoceroses is second only to that of the horses in abundance and completeness. Modern representatives of this family are restricted to Africa, India, Java, and Sumatra, and therefore they seem quite foreign to the North American continent. Yet rhinoceroses were very much at home here during most of Tertiary time, and there is even evidence that they originated in the western United States. They migrated to all parts of the world except South America and Australia.

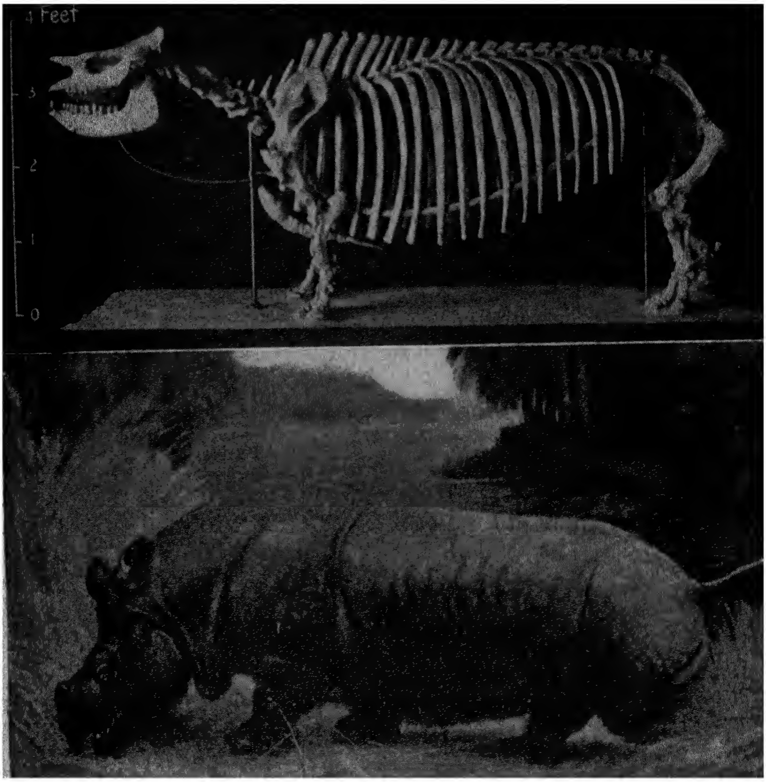

Fig. 374 The short-legged barrel-bodied rhinoceros (*Teleoceras*) that inhabited stream valleys of the western Kansas and Nebraska plains in Late Tertiary time. (*American Museum of Natural History.*)

The modern rhinoceroses are large beasts, 4 to 6½ feet high at the shoulders, with long body, short elephant-like legs, and a long head bearing one horn on the nose or one on the nose and another on the forehead. These horns are unlike those of other horned mammals, such as deer or cattle, in that they consist of solid horny substance without a bone core. The horns are not preserved as fossils but the presence of horns and their place of attachment are shown by roughened thickenings

of the skull. Not all ancient rhinoceroses had horns, however, their place in this family being indicated by other characters of skeleton and teeth. The modern rhinoceroses have three toes on each foot, the central one the largest; this is commonly true of the fossil forms but the more primitive had four toes on the front feet. The initial five-toed ancestor is unknown.

The middle Eocene (Bridger) beds contain several species of primitive rhinoceroses (*Hyrachyus*) about the size of a sheep or somewhat larger. The skeletons are interesting because of unspecialized characters and there are many resemblances to the dawn horse. From this or a similar generalized archaic rhinoceros, at least four distinct and divergent lines of descent arose: (1) relatively light-bodied, hornless animals with slender limbs adapted for running (hyracodonts); (2) large-bodied,

FIG. 375.- Skull of *Baluchitherium*. (*American Museum of Natural History.*)

short, and heavy-legged aquatic animals (amynodonts); (3) gigantic long-necked, long-headed hornless forms known only from Asia (baluchitheres); and (4) the true rhinoceroses, which are generally horned.

The Oligocene, Miocene, and lower Pliocene beds of western America contain very abundant remains of rhinoceroses, forming locally veritable bone beds. One interesting rhinoceros that lived in large numbers along streams and marshy areas in western Nebraska and Kansas in late Miocene and early Pliocene time is noteworthy because of his long, large barrel-like body and absurdly short legs (*Teleoceras*).

· Although not known in North America, we may specially notice the baluchitheres (named from Baluchistan, central Asia, where they were first discovered). These are the largest known land mammals, attaining a height of more than 16 feet at the shoulders and a total length of about 25 feet. The head, armed with two powerful tusks, was about 4½ feet long and the neck also unusually extended. The legs were long and the whole appearance somewhat giraffe-like but much heavier. This branch of the rhinoceros group doubtless fed on the foliage of trees. It lived in the late Oligocene or early Miocene. The American Museum

of Natural History expedition to Mongolia recently was fortunate in finding remains of this huge animal.

Titanotheres.—This is an interesting branch of the odd-toed hoofed mammals that appeared in the early Eocene of the western United States, developed rapidly to a culmination in the Oligocene, and then suddenly died without issue. This group is most abundantly represented in North America but is now known also from Asia and Europe. The earliest known representative of this family was a trifle smaller than a sheep, the skull long and narrow, bearing tusks but without horns. The forelimbs had four toes and the hindlimbs three. Later titanotheres ("giant beasts") increased in size to elephantine proportions. The limbs were stout and pillar-like, and, as in the elephant, the short feet were supported by thick pads. The most striking modifications are seen in the skull, which developed bony knobs and eventually great bony paired horns over the nose. With the evolution of horns there was reduction and loss of the tusks, the skull became long, very broad, and strengthened to withstand the impact when the horns were put to use.

FIG. 376.—Restorations of an early and late type of the titanotheres from western North America. The small animal is *Eotitanops* from the lower Eocene beds, the large one *Brontotherium* from Oligocene beds. (*H. F. Osborn, U. S. Geol. Survey.*)

Despite the large bulk of the later titanotheres the brain was very small, not larger than a man's fist, indicating a low order of intelligence.

Chalicotheres.—The strangest of perissodactyls are animals called chalicotheres from North America and Europe, occurring in middle Eocene to lower Pliocene beds. The skull and remainder of the skeleton except limbs and feet are not greatly unlike those of a horse, although there are many differences. The feet are armed with great claws and, when the first specimens were discovered, in disconnected form, they were referred to an order entirely different from that in which the skull had been placed. Complete skeletons now known show that the horselike

body and clawed feet actually belong together. That this grotesque animal fed on plants is plainly shown by the teeth. The claws probably served in grubbing roots and tubers. Some of the chalicotheres considerably exceeded in height and bulk a good-sized horse (see Fig. 389).

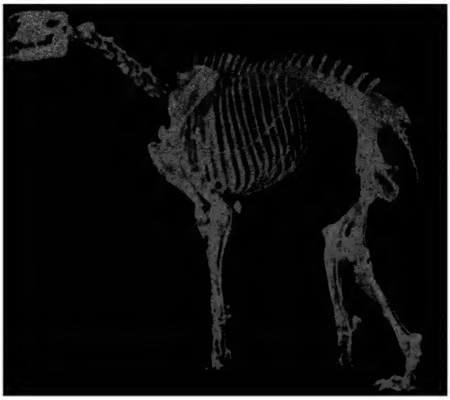

Fig. 377.—Skeleton of a chalicothere (*Moropus*) from Miocene beds of western Nebraska.

THE EVEN-TOED HOOFED MAMMALS

The great group of even-toed hoofed mammals, or artiodactyls, is distinguished by characters of the limbs and teeth that separate them readily from the odd-toed mammals and yet serve clearly to show relationship between such apparently unlike animals as the pig, camel, deer, giraffe, and hippopotamus. The axis of the foot lies between the third and fourth digits, which are equal in size and symmetrical. The number of toes is four or two, although in some primitive forms a vestige of the fifth toe remains. A peculiar and very characteristic structure of the ankle bones is found in all of the artiodactyls. There are two types of chewing teeth, the more primitive having conelike cusps and the more specialized showing crescent-shaped grinding ridges of enamel.

The even-toed hoofed mammals are very abundantly known as fossils, the remains of different kinds being found in each of the Cenozoic stages from lower Eocene to Recent. They appear to have originated in the Old World, where they are most numerous and varied, but migration to the Western Hemisphere brought many kinds to North America. The deer, antelope, bison, and others were well established when man came to this continent. Recent discovery in a Nevada cave of camel remains, showing dried skin, flesh, and sinews, suggests that the last of the native North American camels survived into Late Quaternary time and may have been exterminated by man.

Oreodonts.—The most common kind of mammals in some of the Oligocene deposits of the western United States are extinct creatures

with the size of a small sheep and combining certain characters of pig, deer, and camel. They are called oreodonts. These animals are restricted to North America and are known from Eocene to early Pliocene times. There are many different kinds. During part of their career they must have roamed the plains and river valleys in enormous numbers.

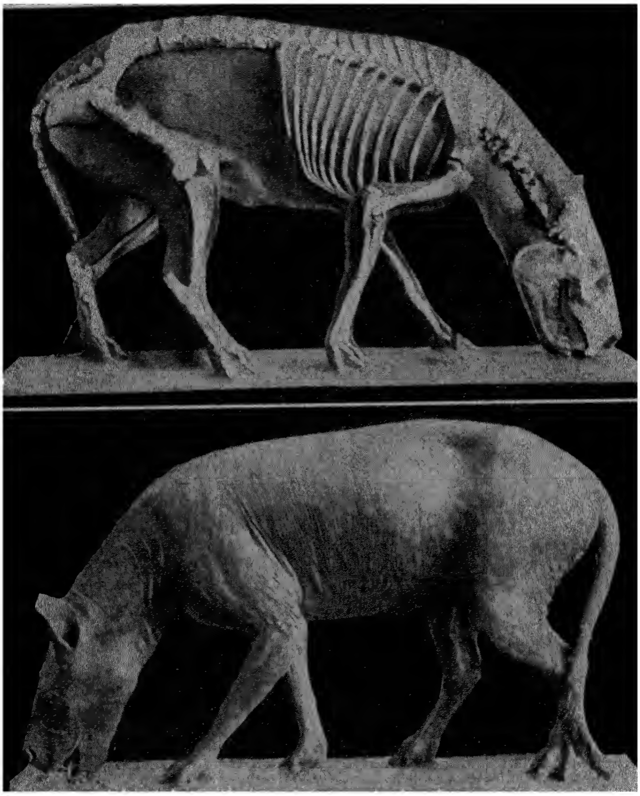

FIG. 378.—Skeleton and restoration of an Oligocene oreodont (*Merycoidodon*) from western Nebraska. (*R. S. Lull, Peabody Museum of Natural History, Yale University.*)

Skeletons are frequently found in little-disturbed condition. An interesting specimen mounted by students at the South Dakota School of Mines shows the well-formed skeleton of an unborn young oreodont as discovered within the body of the mother.

Giant Pigs and Peccaries.—The swine may claim rank as one of the "first families" of the Tertiary. They trace their ancestry into Eocene times and were represented in North America as late as the Pleistocene by large, highly developed peccaries. The strangest, or at least the most uncouth, of the artiodactyl stock are giant pigs (entelodonts) that lived in the Oligocene and early Miocene epochs. These attained a height of 6 feet at the shoulders and were exceeded in

bulk among members of the swine family only by the hippopotamus. The skull of the giant pig was very elongate and it bore peculiar bony excrescences below the eyes and on the under side of the jaw. There

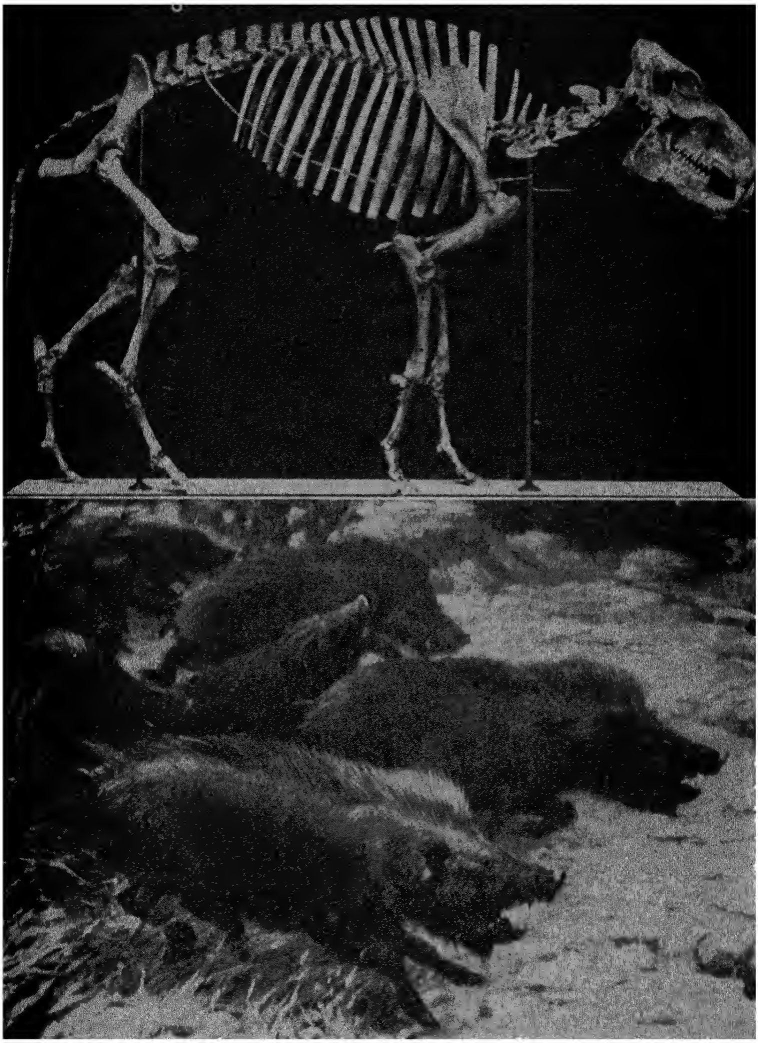

FIG. 379.—An early Pleistocene peccary (*Platygonus*). (*American Museum of Natural History.*)

were stout but not long tusks. The brain was almost reptile-like in its diminutive size; the animal must have been profoundly stupid (Fig. 389).

Camels.—The desert regions of central Asia and northern Africa are the home of one living genus of camels and the cold parts of South America of the other (llamas). The ancestral dwelling place of this

family, however, was North America. The camels appear to have originated here, developed gradually along various lines, increasing greatly in size and in specialization of teeth and limbs. Late in the Tertiary period they migrated to the Old World and into South America, while after mid-Pleistocene time they became extinct in the continent of their birth. The earliest known camels, from upper Eocene beds, were

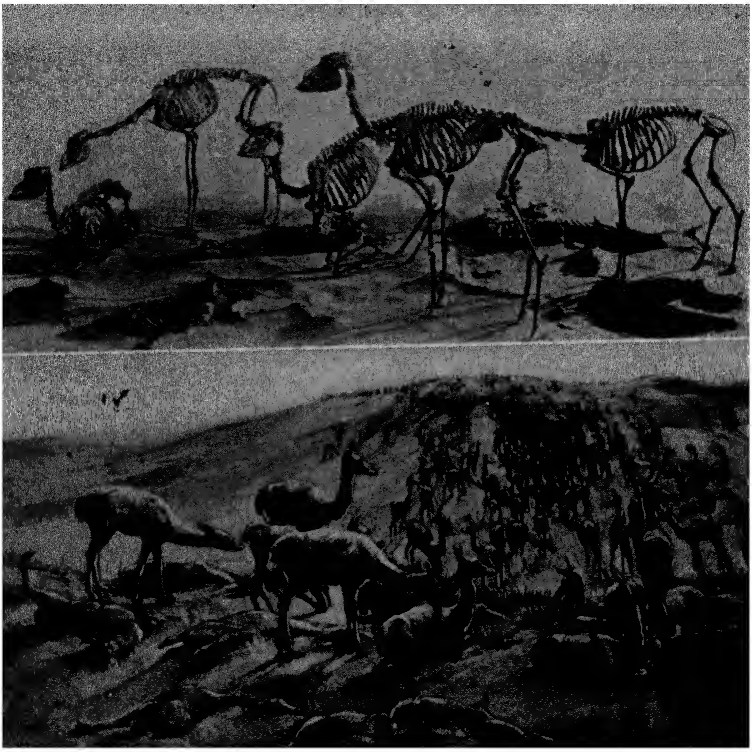

FIG. 380.—Skeletons and restoration of a llama-like camel (*Stenomylus*) that roamed the North American plains in large numbers in Miocene times. (*American Museum of Natural History.*)

smaller than a tiny lamb. The forefoot had four toes but the hind foot was already so modified that there were only two functional toes, although vestiges of two others are present. The development of the camels shows many interesting parallels with that of the horses, but the irreducible number of toes on each foot is two instead of one. Some of the mid-Tertiary American camels were slender, graceful creatures resembling antelopes, and one kind is distinguished by its extremely elongated neck and long legs, an adaptation like that of the giraffe for browsing on leaves of trees.

Deer and Cattle.—Interesting representatives of the deer family are found as fossils in the American Tertiary as far back as the Oligocene.

Some were hornless, others had short pronglike horns, and still others had antlers with branches. One very peculiar group, which is really distinct from the true deer, had a pair of prominent bony plates or horns above the eyes and another pair on the nose. The moose and caribou are immigrants from the Old World that are first known on this continent in Pleistocene times.

The cattle family is represented in America by the bison, muskox, and wild sheep. Domestic cattle and sheep are derived from Asiatic species and have been introduced in the Western Hemisphere by man. The bison, which roamed the plains in such enormous herds before the

FIG. 381.—*Megaceros*, a giant deer of the Pleistocene epoch in northwestern Europe. The head of some individuals was 10 feet from the ground and the antlers had a spread of 12 feet. (*C. R. Knight, Field Museum of Natural History.*)

advance of civilization destroyed them, were present in the Pleistocene epoch but are not known earlier. One kind of fossil bison was distinctly larger than the Recent species and was characterized by a huge hump; another had a horn spread of more than 6 feet. There is evidence that man was contemporaneous with some of these extinct species of bison.

ELEPHANTS

Elephants (Proboscidia) rank with the horse in point of interest and instructiveness of the fossil record. The lineage of this largest living land mammal may be traced far back in Tertiary time and the gradual acquirement of proboscidian peculiarities may be observed step by step. Like the horse and man, the elephant is one of the few kinds of mammals that became adapted to almost all sorts of environments and spread over practically the whole world. Teeth and bones of elephants are found in stream and other deposits of Pleistocene age in almost every part of the United States, testifying to the abundance and wide distribution of these animals in North America until comparatively recent times.

The chief distinguishing characters of the elephants are in the head, which is unusually massive, abnormally shortened, and bears the long powerful trunk. The shape of the skull, the enormously thick but light cranial bones, and the short neck are all modifications that aid in carrying

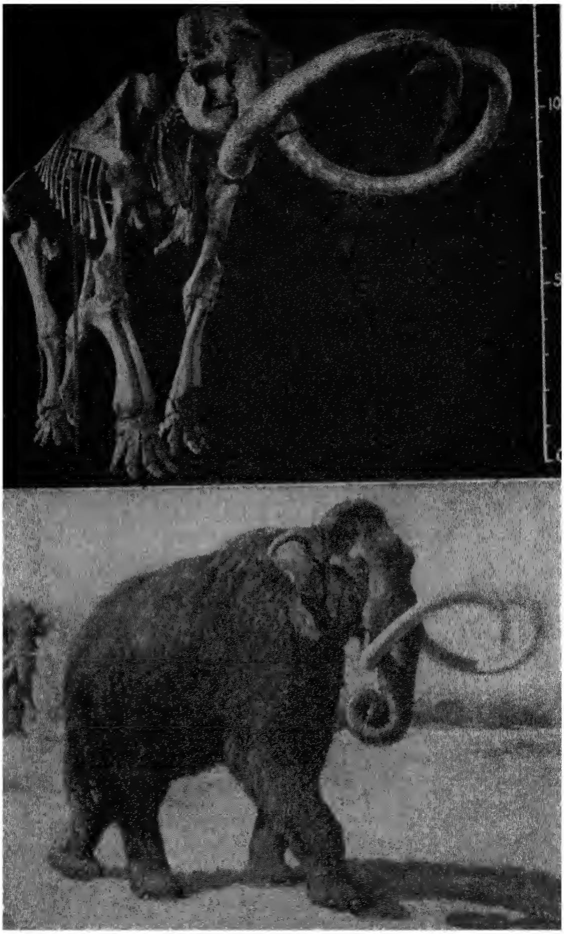

FIG. 382.—Skeleton and restoration of the columbian elephant (*Parelephas columbi*) of the Pleistocene epoch in North America. (*American Museum of Natural History.*)

the weight of the head. The trunk is a very muscular development of the upper lip and nose, the nostrils running the entire length to the tip. Elephants are not the only animals with an elongated proboscis or trunk, but no others have this organ so highly developed. Since elongation of the snout is always correlated with a recession of the nasal bones and with a thickening of adjacent bones for muscular attachment, it is possible to determine from study of a fossil skull whether or not an

animal had a trunk, and approximately how large it was. The teeth of the elephant are distinctive. The tusks are remarkably enlarged long incisors, which in the African elephant may exceed 10 feet in length, 2 feet in circumference at the base, and weigh 230 pounds or more apiece. Some of the fossil elephants had tusks 13 feet, or exceptionally even 16 feet, in length (Lull). The grinding teeth are very large and there is normally only one tooth on each side of the upper and lower jaws. However, as a tooth is worn down to the roots it is gradually displaced by a new tooth that pushes in from behind. Thus the grinding teeth grow in successively, the last or backmost molars appearing at about age forty-five and serving for the rest of the animal's life. The character of these teeth differs notably in different species, that of the modern Indian elephant having numerous parallel grinding ridges, that of the African elephant having a simpler pattern, and those of several extinct forms showing a series of large conelike cusps.

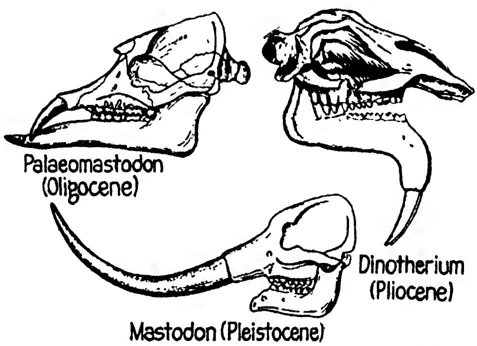

FIG. 383.—Three types of fossil elephant skulls. *Palaeomastodon* with tusks in upper and lower jaws, *Dinotherium* with down-curved tusks in lower jaw but none in the upper, and *Mastodon* with large tusks in upper jaw. (*After Lull.*)

Evolution of the Elephants.—The earliest definitely distinguishable representative of the elephant family is *Palaeomastodon* from the lower Oligocene of northern Africa and southern Asia. This animal had about the size and build of a small modern baby elephant, but the trunk was undoubtedly very short, the head and neck relatively more elongate, and all of the grinding teeth were present at the same time. There were short downward-curving tusks in the upper jaw and very short tusks also in the long lower jaw.

Another north African animal, *Moeritherium*, from upper Eocene and lower Oligocene beds, is cited as a possible ancestor of *Palaeomastodon* and other elephants, but clearly defined proboscidean characters are lacking. This animal had a height of about 3½ feet. The skull indicates that there was no trunklike elongation of the snout at all.

In Miocene times, elephants are known to have spread to Europe and North America, and there are very different kinds. One type

(*Dinotherium*) which occurs in Europe and Asia had no tusks on the upper jaw but on the lower there were large tusks curving downward and backward. Other kinds had four large fairly straight tusks, two on the upper jaw and two on the lower. Some of these are found in North America. They continued into the Pliocene epoch, a specimen of this age from Nebraska having a lower jaw and flat shovel-like tusks at least 6 feet long (see Fig. 365).

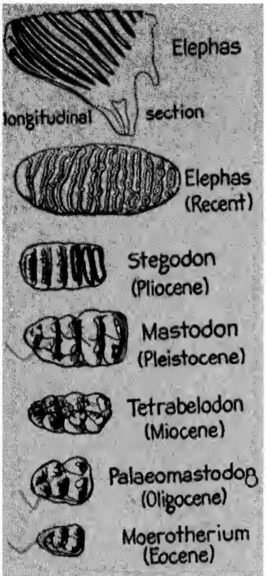

Fig. 384.—Types of elephant teeth, showing evolution in size and in type of grinding surface. (*Modified from Lull.*)

The most abundant and best-known fossil elephants in North America are those of the great Ice Age. Several species are recognized. One type, called the American mastodon, is distinguished partly by the large-cusped grinding teeth which differ markedly from those of the true elephants. The mastodon had about the height of the modern Indian elephant but was much stockier. It was apparently a forest-dwelling animal. Its remains have been found chiefly in drainage excavations in boggy lands of the northern states, one specimen found in New York having a quantity of long shaggy dark brown hair with the bones. True elephants are represented in North America by the imperial elephant (*Archidiskodon imperator*), which had remarkably long

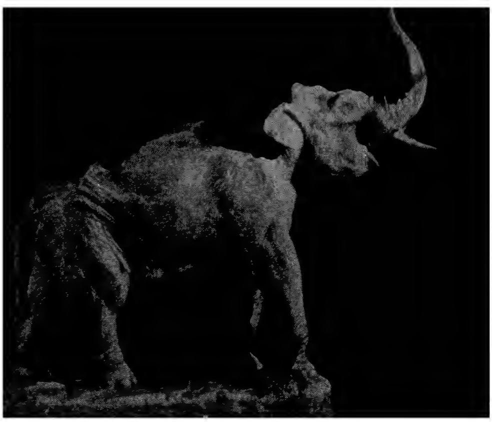

Fig. 385.—The largest of the elephants *Archidiskodon imperator* (the imperial elephant) of the Pleistocene epoch in North America. (*C. R. Knight, American Museum of Natural History.*)

curving tusks and attained a height of 13 feet, the columbian elephant (*Parelephas columbi*), which was somewhat smaller than the imperial, and

the hairy or woolly mammoth (*Mammonteus primigenius*). This last was circumpolar in range, being known in Europe and northern Asia as well as in this continent. It had a thick coat of coarse long black hair with a dense brown wool covering beneath. Two specimens of this animal have been discovered frozen in the Siberian tundras.

The main evolutionary changes in the development of the elephants are increase of size, modification in shape and structure of bones of the skull, loss of incisors and canines except two incisors of each jaw (or of one jaw) that are modified as tusks, increase in size and complexity of the grinding teeth, their reduction in number, and development of the peculiar method of tooth succession, and the growth of the trunk.

CARNIVORES

The carnivorous mammals, including chiefly the cat and dog families, are distinguished by clawed feet and by teeth adapted for grasping and cutting flesh, the long sharp canines and shearlike molars. In the early part of Tertiary time, primitive flesh eaters called creodonts were prominent. These are generalized creatures that resemble in some respects the early hoofed mammals but in others indicate ancestral relation to the specialized carnivores. Primitive characters of the creodonts are seen in the large number, relatively small size, and only partially modified character of the teeth, and the very small brain with few and simple convolutions that indicates low intelligence. Creodonts of North America disappeared in Oligocene time, and those of the Old World in early Miocene time (unless the modern *Otocyon* is really a holdover of the creodont line). Other carnivores, undoubtedly derived from the creodonts, developed along various lines (see Fig. 364).

The best-known cats of Tertiary time are the saber-toothed tigers, characterized by unusual enlargement of the canines of the upper jaw. Evidently, these animals were ferocious beasts of prey that ranged over the whole Northern Hemisphere and late in the Tertiary extended to South America. A very interesting series of skeletal remains from Oligocene to Pleistocene formations reveals the evolution of the sabertooths. Noteworthy are a gradual increase in size of the body, specialization and enlargement of certain teeth, and reduction of the total number of teeth. The culmination of this race is found in the Pleistocene cat called *Smilodon*, whose upper canines were great curved scimitar-like blades, 8 inches or more in length. It is hard to understand how these great tusks, blocking entrance to the mouth, could have been used effectively unless the creature could open its mouth much more widely than any living mammal, and it is very doubtful that the tusks were used in striking at prey, as a snake does with its fangs. There were one or two large cutting teeth at the back of the upper and lower jaws, but other teeth were unimportant or lacking—indeed the entire dentition

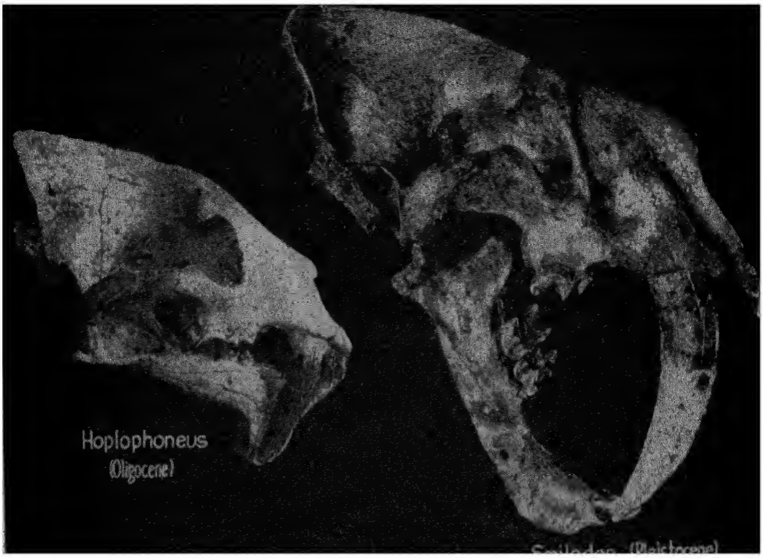

Fig. 386.—Skulls of Tertiary saber-toothed cats. Note the projections of the lower jaw of *Hoplophoneus* to match the extended upper canine tusks. *Smilodon* represents the extreme of specialization of the saber-toothed line. (*American Museum of Natural History.*)

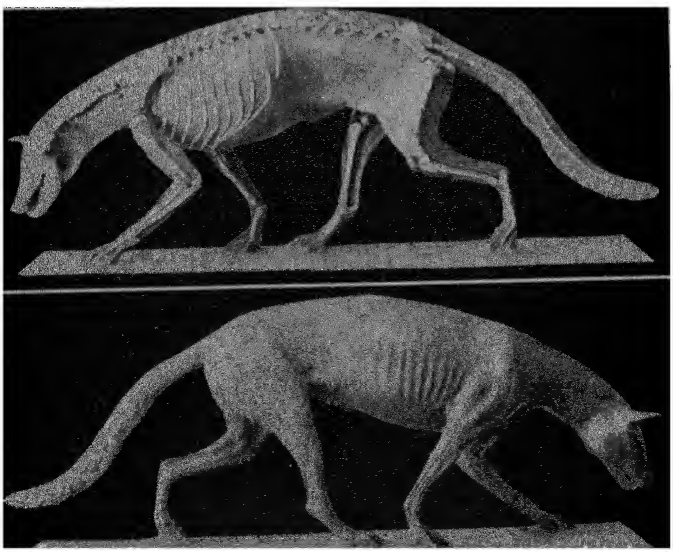

Fig. 387.—A Miocene dog (*Daphaenus*) from western Nebraska. (*R. S. Lull, Peabody Museum, Yale University.*)

includes but 12 to 14 teeth. The form and structure of the skeleton indicate an unusually powerful animal.

Fossil dogs are well-known from the Pleistocene and later Tertiary, but the doglike animals of earlier time are increasingly generalized and show similarities to other carnivores. Dogs are the oldest and probably the central line of carnivore evolution among the mammals. Several lines of development among carnivores became extinct during the Tertiary.

Succession of Mammalian Faunas

We have considered the characteristics and some of the main lines of development of the mammals. It is desirable also to note the grouping of these animals which distinguish the different epochs of Cenozoic time.

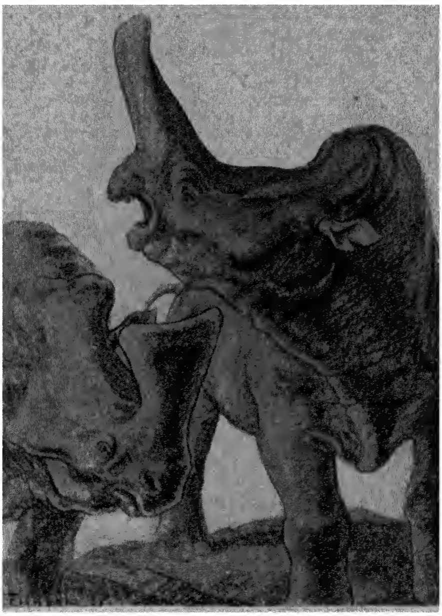

FIG. 388.—A shovel-horned titanothere (*Embolotherium*) from the early Tertiary deposits of Mongolia. (*American Museum of Natural History.*)

Eocene.—Fossil mammals of the Eocene epoch are broadly characterized by their archaic, primitive nature, generalized skeletal structure, and relatively low intelligence. Hoofed animals include the condylarths, which were probably ancestral to the odd-toed ungulates; amblypods, which became increasingly specialized during the epoch and attained the size of a modern rhinoceros; titanotheres, which are hornless and smaller than their Oligocene successors; ancestors of the pig family; and diminutive three-toed horses. Carnivores were represented by the creodonts, some of which in the late Eocene attained large size, one with a skull 3 feet long. In addition, there were some opossum-like marsupials, multituberculates and insectivores, edentates and rodents. Aquatic mammals are represented by large primitive whales called zeuglodonts, some of which attained a length of 80 feet. The primates are represented in the Eocene by lemurs and primitive monkeys.

Oligocene.—Disappearance of many of the very primitive types of mammals, accompanied by rapid evolution of surviving stocks, produced in Oligocene times a mammalian fauna in which most of the now living families had made their appearance. Among the hoofed mammals, changes in form and increase in numbers and variety, specialization of the limbs for more speedy locomotion, and modification of the teeth for grazing on tough grasses of the plains rather than browsing on forest leaves, all indicate a dwindling of Early Tertiary forests and appearance of wide prairie country. The hoofed animals include especially three-toed horses that are distinctly larger than the ancestral Eocene type, primitive running and aquatic rhinoceroses, ponderous titanotheres which in this epoch reached a culmination of size and specialization of long, low horn-bearing skull, entelodonts or giant hogs, the cud-chewing swinelike animals called oreodonts, camels, and some others. True carnivores, including both ancestral dogs and cats, are found in the Oligocene. Rodents related to the squirrels,

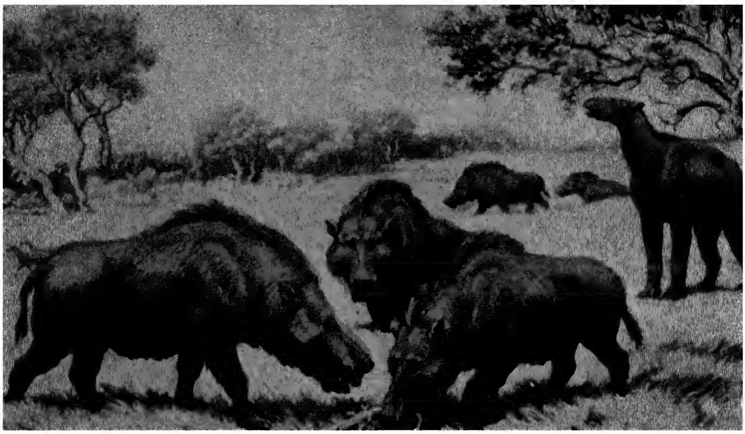

Fig. 389.—Miocene giant hogs (entelodonts) about 6 feet high at the shoulders, and a chalicothere, inhabitants of the western Nebraska plains. (*C. R. Knight, Field Museum of Natural History.*)

beavers, gophers, rabbits, mice, and so on, are common. In the Old World are the earliest known elephants and anthropoid (manlike) primates, the latter related to the existing gibbon and a possible ancestor of the higher apes and man.

Miocene.—The Miocene mammals are distinctly more modern as a group than those of the Oligocene. Some of the prominent Early Tertiary families like the amblypods and the titanotheres are gone, but among the horses, rhinoceroses, camels, and various other hoofed animals, there is a branching out along many lines, some of which show distinctly modern characters of specialization and size. Mastodons are a characteristic and widespread representative of the elephant family in Miocene time. Carnivores are abundant. Primates are larger and more advanced than their Oligocene ancestors. Altogether, the Miocene contains the most varied and interesting assemblages of mammalian fossils and may be considered to mark the peak of mammal differentiation.

Pliocene.—For mammals as a whole, the Pliocene epoch appears to mark the beginning of decline, but man and the domestic mammals are excepted in this statement. As a whole, the Pliocene mammal fauna is decidedly modern in appearance, for almost every living mammalian type is represented. In addition, there are very many mammals that are now extinct but which had flourished in earlier times. The inter-

migration of many types of mammals between the Old and New World and between North and South America is known to have occurred during this epoch.

Pleistocene.—The great climatic changes accompanied by extensive glaciation in the Northern Hemisphere had an important influence on the development of various mammals. Most of the main lines persisted, but many species became extinct and representatives of certain groups disappeared from North America. An entirely modern type of horse persisted during part of the Pleistocene but later disappeared from North America. The same is true of the elephants and camels, some of which may have been contemporaries of man on this continent. To this epoch belong the smilodons, the most specialized and the last of the saber-tooth cats. The South

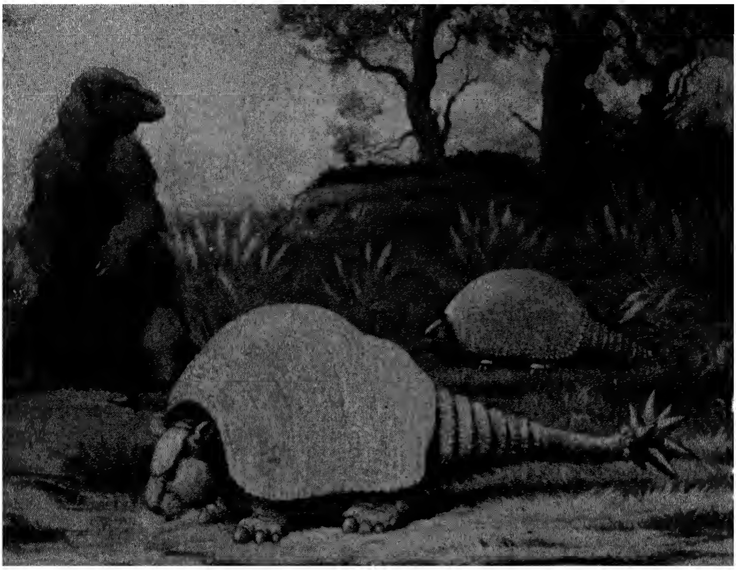

FIG. 390.—Giant ground sloth, *Megatherium* (left) which inhabited South America and southern North America in Pleistocene time. Great armadillo-like mammals, *Daedicurus* (foreground) and *Glyptodon* (right), that were contemporaries of the ground sloths. (*C. R. Knight, Field Museum of Natural History.*)

American Pleistocene mammals include the giant ground sloths, huge armadillo-like glyptodonts, and other creatures that are now extinct.

Man was well established in the Pleistocene epoch, especially in Eurasia and probably Africa. There is evidence that he migrated to North America during this epoch, but remains are much less conclusive in the western world.

Other Vertebrates

The record of vertebrates other than mammals during Cenozoic time is by no means a blank. There are many kinds of fossil reptiles, amphibians, birds, and fishes, interest in these being subordinated to the mammals only because of the remarkable development that the latter show.

Reptiles of the Tertiary and Quaternary periods are distinguished chiefly by their modern appearance. The huge dinosaurs and other strange reptilian creatures of Mesozoic times had disappeared. Their Cenozoic descendants included especially large numbers of turtles of varied kinds, crocodiles, lizards, and some snakes.

Birds are relatively rare as fossils, but several dozen kinds are known from Cenozoic deposits. These represent most of the modern families and some are very close to existing species. There are gulls, ducks, herons, storks, pigeons, grouse, owls, hawks, parrots, and a great many others. Among ostrich-like birds are some of very massive build that attained the gigantic height of about 10 feet; and there is one (*Phororhachis*) with a powerful hooked beak and skull that measured 2 feet in length.

Amphibians were relatively no more important in the Tertiary and Early Quaternary periods than now. Fossil salamanders, frogs, and toads occur.

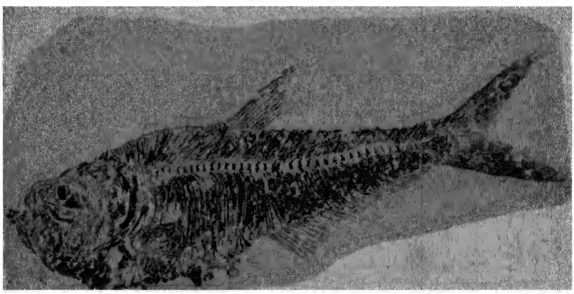

FIG. 391.—A well-preserved fish skeleton from the Green River Eocene beds of southwestern Wyoming.

Fishes.—The chief characteristic of Cenozoic fishes is the rise of the so-called teleosts, or bony fishes, to a position of strong dominance, for they outnumber all other kinds of fishes together more than 20 to 1. The teleosts include the salmon, herrings, carps, perches, mackerels, and many other familiar and some extinct groups of marine and fresh-water fishes.

A famous Eocene fish fauna in western North America is that of the Green River beds in southwestern Wyoming, where large numbers of beautifully preserved complete skeletons have been collected. Similar specimens have been found in the fresh-water Pliocene deposits of western Kansas, and marine fishes are known from several horizons and localities on the east and west coasts of the United States. Europe furnishes a number of fossil fish deposits that have yielded a great variety of fine material. Among the marine fishes, special mention may be made of sharks (*Carcharodon*) that had sharp-edged triangular cutting teeth up to 6 inches long. Based on comparison with the similarly shaped teeth of living sharks it is estimated that some of these Tertiary fossil species attained a length of perhaps 80 feet.

zoic and in present seas the cheilostome bryozoans of complex structural design are strongly dominant.

Brachiopods declined greatly in the Mesozoic era and are even less important in the marine faunas of Cenozoic time. The number of known genera and species in the Tertiary formations is roughly comparable to that of the present day, and the kind of shells, mostly loop-bearing terebratulids and lime phosphate inarticulates, is like that of modern types. They are not significant in correlation of the strata.

Sponges and Corals.—Since the marine Tertiary deposits that have been studied are almost entirely of shallow-water origin, it is not surprising to find few siliceous sponges, for these live chiefly in deeper water. However, only detached spicules of calcareous sponges are found. One of the two orders of calcareous sponges apparently became extinct at the close of the Cretaceous period.

The corals of Cenozoic time are abundant and highly varied. Many new genera and some new families appeared, while some of the families of Mesozoic beginning have their greatest development here. As has already been noted, they belong to the group called Hexacoralla because of their dominant sixfold symmetry. Coral reefs are found in the Eocene of Georgia, Florida, Alabama, Mexico, Central America, and the West Indies, and they occur in rocks of this age in parts of the Old World. Elsewhere are common but scattered occurrences of coral specimens. In the Miocene, Pliocene, and Pleistocene deposits, coral reefs appear more and more restricted toward the tropics, which may be correlated with the gradual lowering of the temperature of the waters.

CENOZOIC PLANT LIFE—THE AGE OF FLOWERING PLANTS

Culmination of Flowering Plants.—All collections of fossil plants from Cenozoic deposits show marked similarities to existing floras. The flowering plants or angiosperms, which made their appearance in the latter part of the Mesozoic era, have assumed very definite leadership. As observed by Knowlton, in an astonishingly short time, geologically speaking, this group has not only come to outnumber all others but it has spread over practically the entire earth, adapting itself alike to the sweltering heat of the tropics and the bitter cold within five or six degrees of the Pole; to sea level or hundreds of feet below in certain inland basins, and to mountain heights of 14,000 feet or more; to regions with an annual rainfall of 500 inches and burning deserts where rain may fall only at intervals of years. Some find a congenial home in marshes, while others have waded boldly into the water and compete with the algae. In size they range from adults scarcely 1/12 inch long to the redwood big trees of California which have a diameter up to 30 feet and attain a maximum known height of 340 feet. In length of life they range from herbs that die in a summer to trees like the baobab that may survive for several thousand years. The variety seems illimitable.

Most of the Eocene genera are the same as today, but the species were different from those in later Tertiary epochs and from living forms. The Miocene and Pliocene deposits contain many plants that apparently have persisted without noticeable change, while Pleistocene time, though little known as regards fossil plants, was undoubtedly characterized by nearly the same flora as that now found on the earth. Altogether,

the Cenozoic era is noteworthy because of the culmination of flowering plants. The floras are all very modern in appearance.

Eocene plants are known in North America chiefly from (1) Greenland, (2) the southern Atlantic and Gulf Coastal Plains, (3) the Western Interior, extending from New Mexico northward through the Rocky Mountains belt into Canada, and (4) the Puget Sound district in western Washington.

Greenland has now an Arctic flora consisting largely of small herbaceous plants, but coal-bearing shale deposits on the western coast show that in Eocene time marshy swamps and forests existed there, in which most of the plants are about like those now living in Virginia or the Carolinas. Nearly three hundred species have been described in this Greenland flora, including the bald cypress, sycamore, magnolia, willow, cottonwood, sweet gum, elm, oak, maple, and many others. This assemblage clearly indicates a rather mild temperate climate.

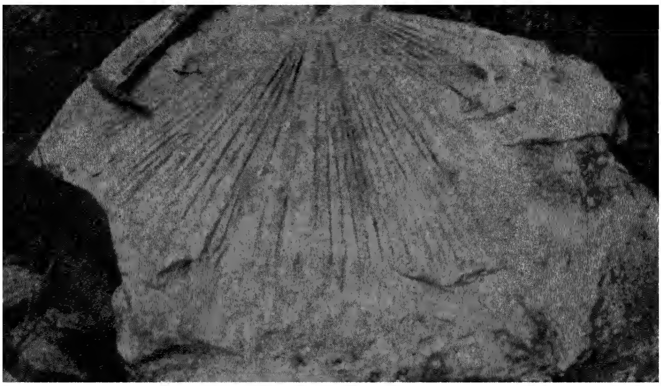

FIG. 396.—Large fan-shaped leaf of an Eocene palm that grew in Montana. (*R. C. Moore, U. S. Geol. Survey.*)

The southern Atlantic and Gulf Coast area contains more than six hundred described Eocene plants, representing three main stages that are each distinct. The oldest (Wilcox) has many species that are related only to plants now living in Central America, northern South America, or the West Indies. There are several palms, figs, laurels, magnolias, cinnamons, and at least two species of the breadfruit tree that is now confined to the Old World tropics. After the Wilcox flora, a considerable time elapsed before appearance of the middle Eocene (Claiborne) flora (as indicated by the nearly complete change in the species), but the interval from this to the upper Eocene (Jackson) plants was not so great. The vegetation shown by the fossils from these horizons is typically that of a warm, low coastal plain, with lagoons, swamps, and estuaries. Besides trees like the cypress and numerous hardwoods, and palms of several types, there were tall reedlike grasses, pond weeds, and dense growths of swamp ferns. The mangrove was locally common.

The Continental Interior contains widespread remains of an early Eocene assemblage of plants, about the same in age as the Wilcox flora of the Gulf region but possibly differing slightly in different places. The plant-bearing beds occur in the Raton formation of northern New Mexico and southern Colorado, in the Denver formation near Denver, and in the extensive Fort Union strata in areas farther north. Since great deposits of coal were formed at this time in this region, it is evident that swamp conditions persisted widely. There were several kinds of palms, including some with

broad fan-shaped leaves 4 or 5 feet across, and these lived abundantly as far north as Montana. About 20 kinds of fig trees are known, a large-leaved breadfruit tree, sweet gums, laurels, cinnamons, and many others. In the more northerly areas, cottonwoods, sycamores, and the various forest hardwoods were relatively most common.

The Puget Sound region of western Washington likewise contains early Eocene coal beds and an interesting flora of about three hundred species very similar to that of the Fort Union beds. Large palms were common. At one place their leaves, some of them 5 feet across, are so abundant that a bed 1 foot thick is almost entirely composed of them. The Puget flora extended northward into Alaska and may have been continuous with that of Greenland.

Abundant Eocene floras are known in Oregon and California, the latter including especially an interesting assemblage of plants from the auriferous gravels that contains many species of the Gulf Coast Wilcox beds.

Oligocene Plants.—Little is known definitely of Oligocene land plants, for there are few fossil-bearing deposits. The widespread Bridge Creek flora of redwoods, which was originally regarded by Chaney as belonging to the Oligocene, is now considered by him to be of early Miocene age. In general, there is evidence of a rather cooler climate and most of the species known are slightly different from those in the Eocene beds.

Miocene Plants.—Miocene time is represented by three very interesting, extremely well-preserved, and extensive floras in the western part of the United States, in Colorado and Washington-Oregon, respectively, and by a small, fragmentary assemblage of plants in Virginia. The last occurs in marine beds (Calvert) at the edge of the low coastal plain of the time and contains only such things as might be washed or blown into the water. Some 26 species are known in all.

The Colorado plant beds afford a very much better glimpse of a Miocene flora, for in a shallow lake that existed at this epoch in a place near the present town of Florissant, west of Colorado Springs, hundreds of thousands of plant impressions and a nearly equally rich record of insects and other forms of life were inscribed in volcanic ash and fine muddy sediments that accumulated in paper-thin layers on the bottom. Some 250 species of fossil plants are known from Lake Florissant. Aside from various water plants, like the floating pond weeds, cat-tails, sweet flags, and reeds, there are many shrubs and trees that grew on the flats or slopes about the lake—sequoias with trunks up to 8 feet in diameter, pines, junipers, poplars, ash, holly, hickories, elms, oaks, and many more. A number of the Florissant genera occur today in other parts of the world but they have disappeared from North America.

A very widespread plant assemblage of early Miocene (or possibly Oligocene) age is the so-called Bridge Creek flora. This is a redwood-forest plant group that is now known to occur from California northward to Alaska, in Manchuria and Siberia, in various parts of Europe, and in the Arctic islands. This forest flora is strikingly like that of the modern California redwood areas bordering the coast.

The middle Miocene flora of the Pacific Northwest is well represented by fossils in the Mascall beds of Oregon, the deposits (Latah formation) of a temporary lake near Spokane, Wash., and elsewhere in Idaho, Nevada, and California. About 150 species of plants have been collected, many of them very beautifully preserved. Sequoias like the California redwoods, willows, cottonwoods, birches, oaks, maples, a sumac, and various other plants are represented. An interesting fossil here is the persimmon, which today is native only in southern states east of the Rockies, and another the ginkgo, described in reviewing the Jurassic flora. Apparently the last stand of the ginkgo in North America was in the Miocene of the Spokane region. The Mascall flora indicates a cooler and drier climate than that of the preceding Bridge Creek assemblage.

Mention may be made here of the wonderful fossil plant deposits of Miocene age in central Europe. These are found especially in the environs of Lake Constance, Switzerland, and the nature of the flora and of the containing sediments shows clearly that, instead of the scenic grandeur of Alpine mountains which characterize this region today, the land in Miocene time was a low-lying, partially lake-covered area with a dense forest of woody trees and shrubs, comparable in richness of species to the present-day valleys of the Orinoco or Amazon. Professor Heer, in a monumental work on the Miocene flora of Switzerland, has described 697 species of woody and herba-

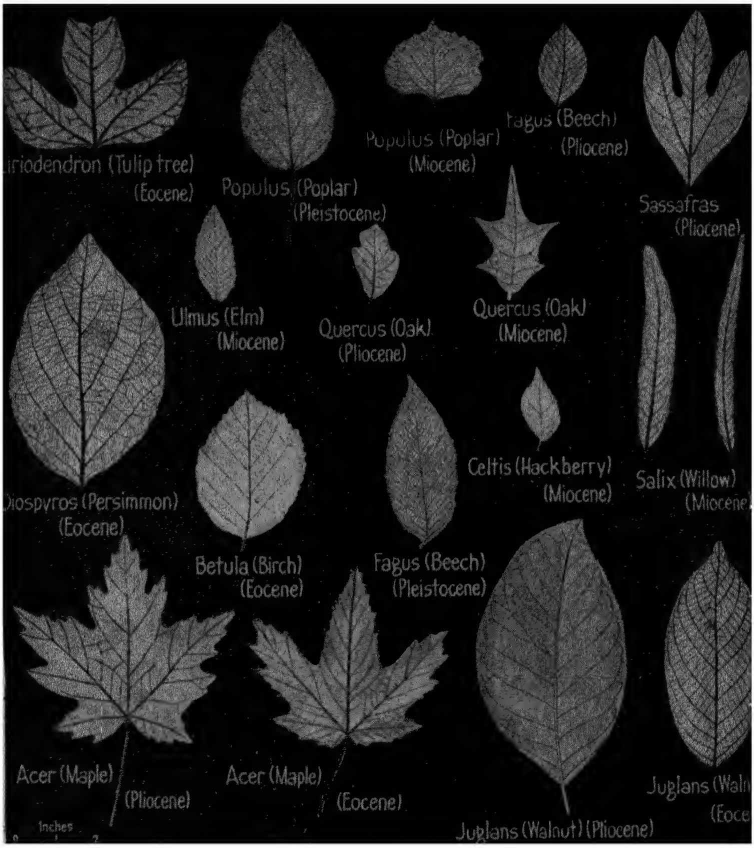

FIG. 397.—Leaves of several types of Cenozoic angiosperms.

ceous flowering plants and a large number of plants belonging to lower groups. The majority of the fossils are very perfectly preserved, showing even the most delicate parts. The presence of a dozen kinds of palms and of other warmth-loving plants is indicative of mild climate.

Pliocene Plants.—The record of plant life in the latter part of Tertiary time and during the Pleistocene is much more scanty in North America than for some of the older epochs. This is evidently due to the relatively high stand of the continent and prevalence of conditions favoring erosion, or at least general absence of land deposition favorable to burial and preservation of plants. Undoubtedly vegetation was about as abundant and varied as in the Miocene or at present.

Pliocene beds of California contain the largest number of fossil plants of this age yet known on the continent. The flora, obtained from several localities, numbers 34 species. These indicate a much cooler and drier climate than that of Miocene time on the West Coast and suggest the diversified conditions resulting from Late Tertiary mountain uplifts in western America.

From the plains region of western Kansas and Nebraska have recently been collected exceptionally preserved fruits of prairie grasses of Pliocene age. These are the first known fossils of this sort. In a few places there are numerous leaves of trees that grew in the stream valleys. Very common are the "stones" of the hackberry.

A small Pliocene flora has been described from Alabama. European Pliocene plants are numerous and fairly well-known. All available evidence points to a gradual lowering of average temperature that presaged the advent of the Pleistocene ice sheets.

Pleistocene Plants.—The glaciers obliterated the vegetation of the north and forced persisting species southward. At stages of greatest advance of the ice, such northern trees as the balsam, fir, and tamarack lived in the central United States, but during interglacial stages when the climate was greatly ameliorated these invaders retreated northward.

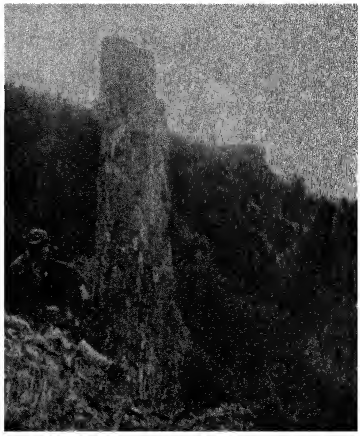

Fig. 398.—Standing trunk of a Tertiary petrified tree, Yellowstone National Park. (*J. P. Iddings, U. S. Geol. Survey.*)

One of the most interesting occurrences of Pleistocene plant fossils is in a clay deposit near Toronto, Canada. The clay overlies glacial till and is accordingly younger than the till. It lies beneath another bed of till that was formed in a still later glacial stage of the Pleistocene. The interglacial plants are found in two main zones. The lower contains remains of the Osage orange, southern white cedar, post oak, pawpaw, and other plants, some of which grow today only in a latitude several hundred miles farther south. The climate around Toronto must have been appreciably warmer at that time than now. The upper zone contains plants of a type that are resident today in northern Quebec or Labrador, indicating a return of the cold that brought about glaciation, as shown by the higher till.

Extensive collections of Pleistocene plants have been gathered in the last few years from California (Chaney). More than 40 species have been identified, most of them still living. The southward extension of the northern forests, probably to be correlated with one of the glacial stages of the Pleistocene epoch, is indicated (Willow Creek flora).

SUMMARY

The Cenozoic era is appropriately termed the "Age of Mammals," because this highest of the vertebrate groups expanded enormously in numbers, variety of form, and intelligence, becoming—as they are today—the dominant animals of the earth.

Mammals are warm-blooded animals, characterized by a hairy body covering and by the nurture of the young through milk glands of

the mother. They originated from reptilian ancestors near the beginning of Mesozoic time but did not assume prominence until the early part of the Cenozoic era, when they began to show specialization along many lines, increase in average size, enlarged intelligence, and a vast expansion in numbers. During the Tertiary period, mammals became adapted to almost every possible mode of life on land, in waters, and in the air. Fossil remains are abundant in many places and the record of mammalian evolution is fairly well-known.

The older Tertiary deposits contain skeletal remains of *primitive hoofed mammals* that are distinguished by generalized structure and low intelligence. Chief types are animals called condylarths and amblypods. They shortly became extinct but are the stock from which the higher types of hoofed mammals are probably derived.

Most important of the *odd-toed hoofed mammals* are the horses, which first appeared in early Eocene time as diminutive animals with four toes on the front feet and three toes on the hind feet, and with short-crowned cusped teeth adapted for browsing. Successively younger representatives of the horse line show gradual increase of size, reduction in the number of toes until ultimately only the middle one remains, and important changes in the form of the teeth and skull. Horses became extinct in North America during Pleistocene time. Other odd-toed hoofed mammals that are well represented in the fossil record are the rhinoceroses, which were greatly varied in form and very rich in numbers, the titanotheres, an extinct race of strange horn-bearing elephantine creatures, and the chalicotheres, large and peculiar claw-toed herbivorous animals.

The group of *even-toed hoofed mammals* includes a host of swine- or sheeplike oreodonts, giant hogs called entelodonts, peccaries, camels of various sorts, deer, and cattle. Each of these shows evolutional change along different lines, some leading to modern species and others to extinct branches.

Elephants were formerly numerous in North America, although they appear to have originated in the Old World. The gradual development of structural peculiarities, especially of the teeth and form of the skull, are well shown by fossil species coming from different parts of the Cenozoic deposits.

Carnivorous mammals, particularly the dogs and cats, are well-known from Tertiary and Quaternary formations but their remains are very much less common than those of herbivores. The saber-toothed cats that culminated in the Pleistocene *Smilodon* are especially interesting.

The successive mammalian faunas from Eocene to Pleistocene time show progressive changes from the archaic, primitive stocks of the Early Tertiary to the highly specialized and widely differentiated groups of the Quaternary. There are numerous extinct families and races. Each

epoch is distinguished by characteristic species and association of mammal types. The peak of mammalian development, excepting man, may be recognized in the Miocene fauna.

Among the *lower vertebrates* of Cenozoic time are (1) reptiles, including especially turtles, crocodiles, and lizards, (2) birds, which contain representatives of most modern families, (3) amphibians, and (4) fishes, which are distinguished by dominance of the teleost or bony fishes and among marine forms by the very large size of some sharks.

Invertebrates are distinguished by the prominence of pelecypods and gastropods. Protozoans are very abundant and varied, and there are many kinds of echinoids, bryozoans, and corals. In general, the Cenozoic shells are very perfectly preserved, in some cases showing practically no alteration from their original condition. The number of species is very large.

Cenozoic plants are very numerous and in several deposits remarkably well preserved. The flowering plants or angiosperms far outrank all others in interest and importance.

CHAPTER XXX

THE GEOLOGIC HISTORY OF MAN

Man is an animal. We may say without egotism, however, that he is the most remarkable animal of known earth history—that he marks the supreme achievement of the organic world. Not only has mankind gained conquest over all the lands of the earth, but he has devised means of traveling at will over the surface of the waters, beneath the seas, and in the air. The multiplicity of his physical works and inventions, the complexity of his social organizations and adaptations, and his development along many lines of so-called cultural and spiritual advancement are sufficient grounds for regarding man as truly unique.

But does mankind stand really alone? Is he a superior being wholly unrelated to other forms of life on the globe? These questions have often been asked and are pertinently raised here. In answer, we find that study of man's body discovers nothing that is really significant as a basis for complete separation from various other kinds of living animals. The plan of his skeletal and muscular organization is the same. Part for part and organ for organ, there is such complete and detailed correspondence that, whatever man's ancestry, we must conclude that he is fashioned after the pattern of so-called lower animals. The chief distinguishing feature of man is his brain. Structurally, he is otherwise comparatively simple and unspecialized. Each of the limbs bears five digits, which is the primitive number, and the teeth are little altered from those of some archaic Eocene mammals.

Man's closest relatives among existing animals are creatures that similarly have an unusually well-developed brain and little specialization of limbs and teeth. These animals, including man, were grouped by Linnaeus under the term Primates (from the Latin *primus*, first). Zoologists recognize two very unequal groups among the Primates: (1) the Lemuroidea, primitive forms with a narrow foxlike muzzle, and (2) the Anthropoidea, manlike forms, including monkeys, baboons, apes, and man. Externally, there is little indeed to suggest a relationship between man and the lemurs, but the similarity of man and some of the anthropoid apes is well-known to all. Study of existing primates indicates clearly, however, that none of the apes can possibly be directly ancestral to man. They are merely cousins of man—some of them rather distant cousins. The chief evidence of this lies in skeletal specializations of the apes that diverge from structures seen in man. Modifications that are associated

mainly with tree-dwelling habits have carried monkeys, gibbons, orangs, chimpanzees, and gorillas distinctly beyond a point that could give rise to beings like mankind. Yet it is entirely reasonable to presume that all of these have been derived from a common ancestral stock that lived in some part of the fairly recent geologic past. Let us review what is known of fossil primates.

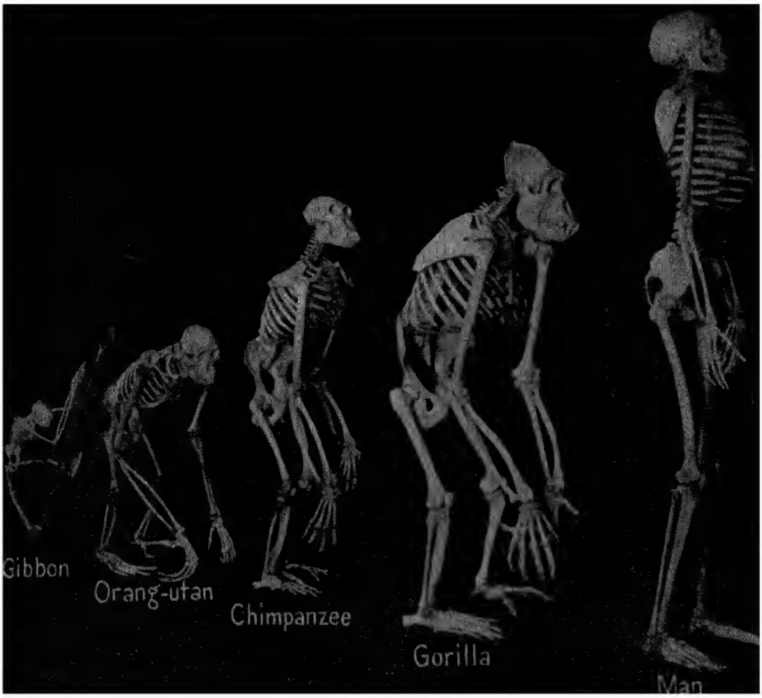

FIG. 399.—Skeletons of modern primates. (*Peabody Museum, Yale University.*)

FOSSIL PRIMATES OF TERTIARY TIME

Eocene.—Primate fossils have been found in all of the continents except Australia. One of the best-known genera is *Notharctus*, an Eocene animal with size about equal to that of a large rat. Its skull is low, long, and rather pointed in front. The teeth are generalized in form, like those of other primitive mammals; their number is larger than in man; the incisors project obliquely forward; and there is a space between the incisors and the molars. The food of these animals probably consisted of fruits, nuts, eggs, and insects. Bones of the skeleton are light and slender, and the structure of the long-toed feet indicates that the animals lived mainly in trees.

There is difference of opinion as to whether *Notharctus* should be classified as lemuroid or primitive anthropoid, but it seems clear that, if

this creature is not the ancestral stock from which both suborders were derived, it is very close to this ancestor. We are not much concerned with the lines of development that lead to the modern lemurs or to the South American and Old World monkeys, but we shall seek to follow the anthropoids that are more closely related to man. It may be noted here that, although at least one nearly complete specimen of *Notharctus* has been found in the Eocene deposits of North America, no fossil primate is known from this continent in Tertiary rocks younger than the Eocene. This forces us to look elsewhere for possible evidence of steps in the evolution of the anthropoids.

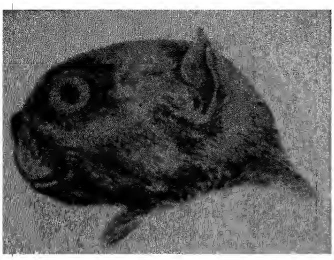

FIG. 400.—Head of monkey-like lemur (*Anaptomorphus*) from the Wasatch Eocene beds of the western United States. (*W. B. Scott.*)

Oligocene.—The Oligocene beds of northern Africa have yielded a number of important fossil anthropoids. One, *Parapithecus*, is decidedly primitive, but there is a slight extension of the lower part of the jaw which foreshadows development of a chin. Another, from a higher

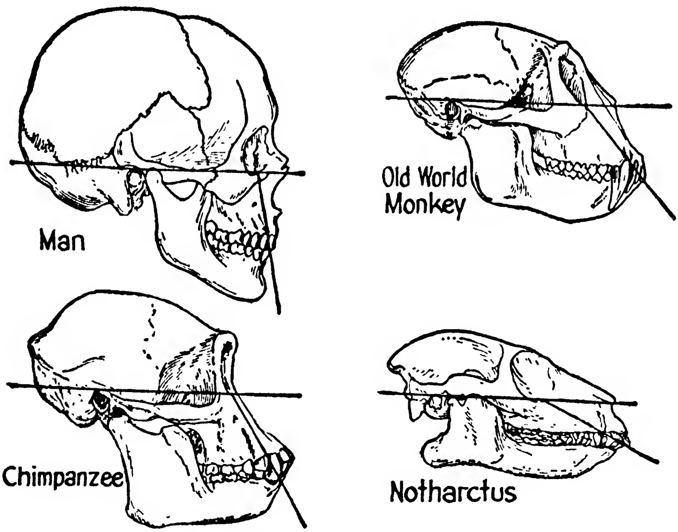

FIG. 401.—The skulls of man and lower types of primates showing proportions of the brain case and facial regions and the facial angle. (*After W. K. Gregory, from K. F. Mather, Sons of the Earth, W. W. Norton & Company, Inc.*)

horizon, is *Propliopithecus*, which is a generalized but more advanced form that might well have served as the ancestor of all of the modern apes, the gibbon, and man.

Miocene.—The Miocene deposits of Europe and Asia contain several fossil anthropoids. One of these appears to belong to the lineage of the

gibbon, another is in the line of development of the orang, and still others are closely related or in part ancestral to higher anthropoids, including man. An interesting genus that is well represented by skeletal remains obtained in India is *Dryopithecus*. Some of the species show a trend toward characteristics of the modern gorilla, and some show a similar trend toward characters of the chimpanzee. At the same time, the structure and appearance of these animals are probably very close to those of our prehuman ancestors in mid-Tertiary time. Relationship to man is especially shown by critical study of the dentition of *Dryopithecus*, which in many details is practically identical with that of man.

Miocene beds of India have yielded scanty fragments of another anthropoid known as *Sivapithecus*. Some authorities believe that this form is even closer than *Dryopithecus* to the primate line leading to man, but this is doubtful.

Pliocene rocks of Eurasia and Africa contain fairly numerous remains of anthropoids. But all of these, with a single exception, are more closely related to existing genera of apes than to man. The exception is a skull, found in 1925, near Taungs, South Africa. The skull was embedded in travertine limestone in a nearly filled old cave, some 50 feet below the surface of the ground. The age of the deposit is doubtful but is thought to be Pliocene or possibly very early Pleistocene. The fossil, which has been named *Australopithecus*, indicates an animal much more manlike than any of the apes. Its attitude was more erect and the poise of the head, as shown by the proportion of brain in front and behind the supporting column, indicates a position intermediate between that of the adult chimpanzee and the most primitive type of existing man. The contour of the face is apelike, but the teeth meet vertically as in humans; the canines are larger than in man but smaller than in the apes; the molars are large and the cusps resemble those of the modern Bushman. Characters of the teeth, therefore, show rather definitely that this animal was intermediate between the chimpanzee and man. The brain case is larger than those of existing apes, but distinctly smaller than that of the most primitive fossil man, or the lowest types of living men. Notwithstanding all of these characters that place *Australopithecus* somewhat midway between apes and primitive man, the South African fossil probably represents an offshoot of the anthropoid line leading to man, rather than a true ancestor of man.

MAN IN THE QUATERNARY PERIOD

Fossil Remains of Man

We come now to the Quaternary period, which from the standpoint of living things is appropriately termed the "Age of Man." During the time in the Pleistocene epoch when great ice sheets spread over much of

the Northern Hemisphere, and during the interglacial stages of comparative warmth, there lived in Asia, Africa, and Europe various genera belonging to the immediate family of man. The middle and later parts of the Pleistocene epoch witnessed the appearance of true man, genus *Homo*. The Recent epoch is characterized by the remarkable development of the species *Homo sapiens*, to which belong the races of modern mankind.

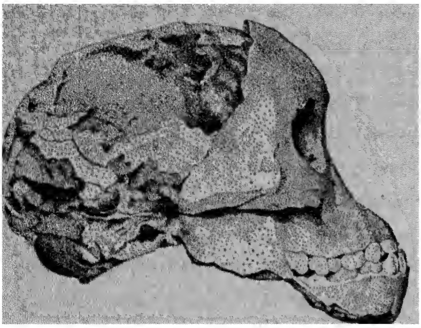

FIG. 402.—Skull found near Taungs, South Africa, which possibly represents an extinct genus of the man family. It is named *Australopithecus*. (*K. F. Mather, Sons of the Earth, W. W. Norton & Company, Inc.*)

***Pithecanthropus*, the "Ape Man."**—Perhaps the most famous, but not necessarily the most important of man's fossil relatives, is the so-called *Pithecanthropus*, or "ape man." Knowledge of this genus is based on the upper portion of a skull, an upper leg bone (femur), and three teeth discovered in 1892 on the banks of Bengawan River, near Trinil, Java. The fossils were in an ancient gravel bed. The associated petrified bones of other animals, together with evidence from fossil plants in overlying and underlying strata, indicate that the deposit was formed in early Pleistocene time.

The chief features revealed by study of the remains of *Pithecanthropus* are the combination of distinctly apelike and manlike characters. The eyebrow ridge is very prominent and massive, as in the gorilla and chimpanzee. The forehead is strongly receding, and the brain case low. Characters of the teeth are distinctly human. The shape and articulating surfaces of the leg bone indicate that its possessor stood in a fairly erect posture. For many years these fossils lay in a museum in Belgium, the matrix not completely removed from the interior of the skullcap, but recently some interesting studies of the brain of *Pithecanthropus* have been made (McGregor, 1925). A cast of the interior of the skull shows accurately the shape of the brain and reveals the location and form of the brain convolutions. This is due to the fact that growth of bone on the inside of the skull follows closely the configuration of soft parts. Measurement of the size of the *Pithecanthropus* brain indicates that it had a volume of about 940 cubic centimeters, which is much greater than that of a large gorilla (about 560 cubic centimeters) and even within the range of low modern humans. Furthermore, the brain cast shows such development of the temporal and other regions as to permit the conclusion that *Pithecanthropus* possessed the rudiments of speech. The apeman genus is believed surely to belong in the family of men, Hominidae, but he is not necessarily a direct ancestor of man.

***Eoanthropus*, the "Dawn Man."**—Another of the oldest representatives of the man family is *Eoanthropus*, or "dawn man." Skull remains of this creature were found in 1911 near Piltdown, Sussex, England, and in 1917 additional material was found in the same deposit some 2 miles from the place of the original discovery. The Piltdown fossils show characters of the lower jaw, some of the teeth, and the brain case, but the facial part of the skull is mostly lacking. The lower jaw is long,

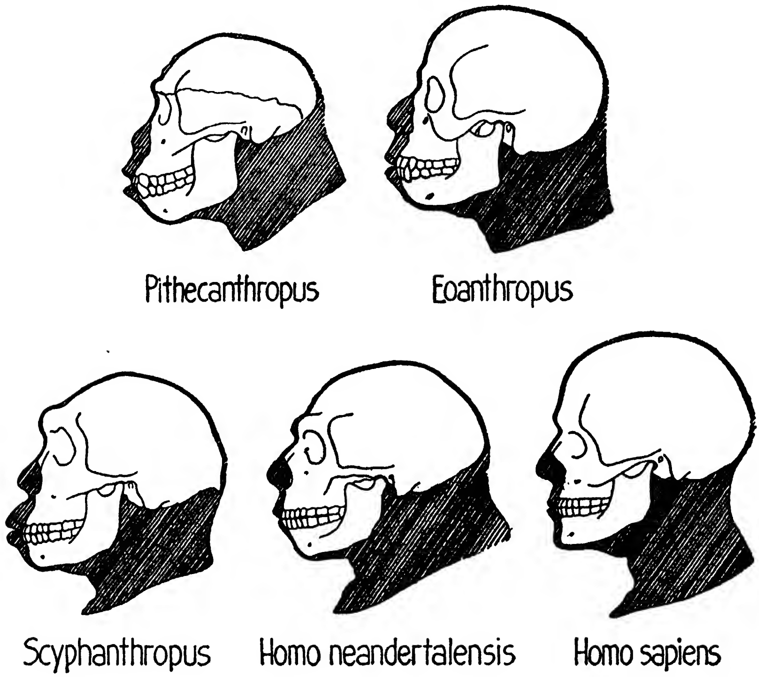

FIG. 403.—Restoration of the skulls of fossil representatives of the man family, Hominidae. (*After McGregor.*)

massive, and, like the apes, chinless. The molar teeth are manlike in general form, but the ridges of the grinding surface resemble those of *Dryopithecus*. The canine is enlarged and more apelike than human. The frontal portion of the brain case is low, but the size of the brain is larger than in *Pithecanthropus*. Remains of extinct species of elephant, hippopotamus, and beaver that are associated with bones of the dawn man indicate a time belonging early in the Pleistocene epoch, possibly a million years before the present.

***Sinanthropus*, the Fossil Man of China.**—A third extinct genus of man is *Sinanthropus*. Our knowledge of him is based on remains found in richly fossiliferous cave deposits some 40 miles from Peiping (Pekin), China, that have yielded an abundance of bones representing early Pleistocene animals. Material excavated in 1928 yielded teeth and

several lower-jaw fragments of an anthropoid, and in the following year special search for additional material of this sort was rewarded by discovery of a nearly complete, very well-preserved skull. This so-called "man of China" is shown to have had excessively massive brow ridges, somewhat like those of the Java ape man, but his brain capacity was about 25 per cent larger than that of *Pithecanthropus*. The fragments of jaw and teeth indicate a heavy apelike jaw, probably with little or no chin, as in *Eoanthropus*.

***Scyphanthropus*, the "Stooping Man."**—Rhodesia, in South Africa, has yielded evidence of a fourth extinct genus of the human family that is probably of middle Pleistocene age. The discovered remains consist of a very thick-boned skull with cranium and facial part well preserved,

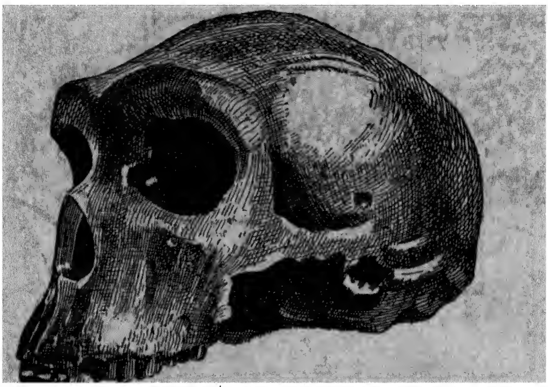

FIG. 404.—Fossil skull of *Scyphanthropus*, from Rhodesia, South Africa. (*K. F. Mather, Sons of the Earth, W. W. Norton & Company, Inc.*)

and part of a pelvis. The shape of the socket for the upper leg bone shows that the pelvis belonged to an individual that stood with a distinct crouch—hence the name *Scyphanthropus*, meaning the "stooping man." The skull exhibits very prominent brow ridges, the forehead is low and receding, and the brain capacity (1,300 cubic centimeters) is larger than the lowest range of existing human beings.

***Homo*, True Mankind.**—Finally, we come to representatives of the genus to which modern man belongs, called *Homo*. The oldest of the true men may well have been contemporary with other genera of the man family that are now extinct, but we do not know this definitely. It is probable that the high plateau region of central Asia is the ancestral home of man, but evidence of the beginnings of his existence in this region has yet to be discovered.

The Birthplace of Man.—The main reasons for belief that central Asia was the region in which the human branch of the primate stock was developed may be stated briefly. (1) Study of the distribution of different animal groups indicates that the primitive members are constantly thrust out from the center of dispersal into the most remote terminal regions of the earth's surface. As applied to man, we find that the

interior of Asia is centrally located with reference to a fringe of the most primitive living peoples, native Australians, Bushmen, Negritos, and Tierra del Fuegans, who have been pushed out into the peripheral regions of the globe as companions of primitive mammals. (2) The great plateau of central Asia, now barren and sparsely inhabited, is bordered on the west, south, and east by the earliest recorded civilizations, those of Egypt, Asia Minor, Chaldea, India, and China. (3) From central Asia came the successive invasions that overflowed Europe in prehistoric and later times, each group of invaders pressing westward and being pressed in turn from behind. The history of India contains similar record of wave after wave of invasion from the north and that of China of many invasions from the west. (4) The most ancient genera of the family of men, in so far as now known, largely surround the central Asiatic area: *Sinanthropus* in China, *Pithecanthropus* in Java, *Scyphanthropus* in Africa, *Eoanthropus* in northwestern Europe, and early representatives of *Homo* in Europe and Asia. (5) The ancestral anthropoid stock from which the family of mankind seems most likely

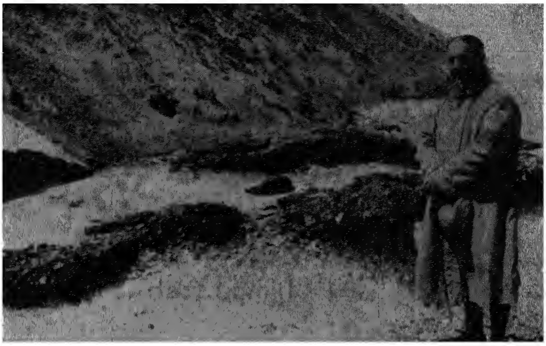

FIG. 405.—Forest bed at Cromer, England, from which relics of early Pleistocene man have been collected. Mr. J. Reid Moir, British archeologist. (*Dean Little, Clark University.*)

to have been derived is Asiatic. (6) Study of the Tertiary geology and paleontology of central Asia indicates that this country was a high plateau region during much of this period, partly open, partly forested, partly well-watered, and partly arid. This is an environment likely to have favored differentiation of a branch of the anthropoid stock leading to primitive man.

Heidelberg Man.—The most ancient fossil that is regarded on competent authority as belonging to true man consists of a lower jaw found in a gravel pit near Heidelberg, Germany. The fossil is accordingly designated *Homo heidelbergensis*. The teeth are distinctly human in character, set nearly vertically in the jaw and without apelike differentiation of the canines. The jawbones show primitive characters in their considerable thickness and breadth, but there is suggestion of the presence of a chin. The age of the gravel bed that yielded this fossil is not determined certainly but is thought to belong to the Mindel-Riss interglacial epoch, which corresponds to that between the Kansan and Illinoian glaciations of America.

Neanderthal Man.—The next race or species of fossil man that lived in the Ice Age of western Europe is well-known, for remains of some 40

different individuals have been found. The first discovery was near the village of Neanderthal, in northwestern Germany, and accordingly the species has become known as *Homo neanderthalensis*. The prominent eyebrow ridges, sloping forehead, and the brain capacity are comparable with those of some prehuman genera, and they likewise suggest some of the most primitive types of living mankind. The chin was somewhat receding, the head was carried well forward, and the posture was not fully erect. Neanderthal man lived in valleys and rock shelters of western and southern Europe in the latter middle part of Pleistocene time, greatest development belonging to the third (Riss-Würm) interglacial epoch, which corresponds to the Sangamon interglacial stage in America. The Neanderthalers were great hunters and they became proficient in the making of various sorts of flint implements. There is also evidence that they knew how to use fire. As the chill of Würm glaciation advanced

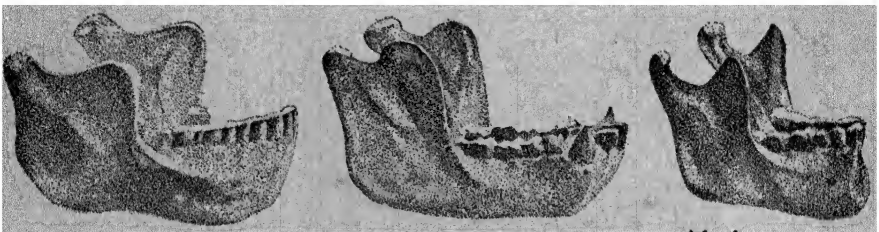

FIG. 406.—The lower jaw of Heidelberg man compared to that of an ape and modern man. (*K. F. Mather, Sons of the Earth, W. W. Norton & Company, Inc.*)

upon them, they were forced to give ground and just what happened to them is not known. They were replaced by a superior race of invaders that is regarded as the oldest known representatives of the existing human species, *Homo sapiens* (the "wise man").

Cro-Magnon and Modern Man.—At about the time when the Würm glaciers were at their maximum extent or beginning to disappear, that is, some thirty to forty thousand years ago, the first known representatives of modern man appeared in western Europe. The best known race is called Cro-Magnon, from a small village in central France (Dordogne region) where numerous fossil bones have been found in caves along the river courses. Several complete skeletons are known, and altogether approximately 75 individuals of Cro-Magnon and other men of about this time are known. The Cro-Magnon skulls have a high forehead, facial bones nearly vertical, a brain capacity fully equal to that of the average modern European, and a well-developed chin. The remainder of the skeleton is splendidly proportioned and indicates that these men stood with erect posture. The average height was somewhat greater than that of modern men. A remarkable record of the cultural achievements of Cro-Magnon man is left in the various tools and ornaments fashioned

from flint and bone that have been found, and in paintings and carvings on cave walls. Physically, this prehistoric race differed in no determinable way from high types of existing men and it was certainly superior to some of the lower ranks of modern mankind.

Implements and Art of Prehistoric Man

Just as the fossilized trail of a worm or track of a dinosaur furnishes definite though incomplete evidence of the existence of these organisms, so all man-made things of prehistoric time are properly considered as fossils. These products of man's activity are collectively termed artifacts. Artifacts are nearly, if not quite, as important as the fossilized bones of man, for they furnish definite testimony of developing brain power and manual skill.

At this point it is appropriate to call attention to the hands of man, for, next to the brain, the hand is his most important individualizing character and asset. Contrary to general impression, man's hand is not a highly specialized structure. Unlike many other mammals in which the number of the digits has been reduced to four, three, two, or even one, man retains the five subequal fingers of the most primitive quadruped stocks. Also, the digits bear no strong impress of special adaptation, as for flying, like the bat, for swimming, like the seal, or for running, like the antelope. The usefulness of the hands of man lies (1) in the fact that his bipedal mode of progression has freed the forelimbs for other uses, and (2) in the modification of the hand for grasping, which is an inheritance from ancient arboreal ancestors. Fortunately, this modification is not too greatly advanced. The apes use the thumb very little or not at all, for they rely on the long strong fingers as they swing from branch to branch. They cannot, like man, oppose the tip of the thumb and each of the four fingers. Thus, the hand of man has not been spoiled by too long a sojourn in the tree tops.

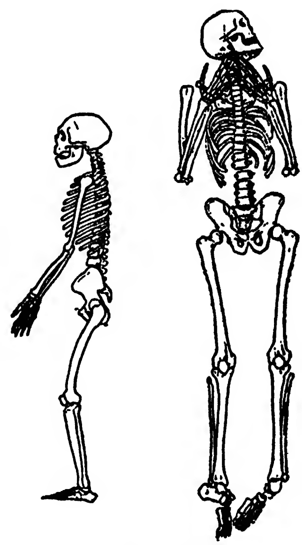

FIG. 407.—Skeletons of Neanderthal man (left) and Cro-Magnon man (right), at same scale. (*After R. S. Lull.*)

Succession of Cultures.—Most of the rock shelters and caves in western Europe that were inhabited by extinct species of men in Pleistocene time are thickly floored by earth and debris, which is the accumulation of many tens of centuries. Excavation of these cave deposits commonly shows a number of successive layers containing various sorts of human artifacts, the traces of ancient man-built fires, and not infrequently

the bones of animals, both of man and of contemporary mammals. The relative age of such deposits is clearly shown by the order of their succession, the oldest at the bottom and the youngest at the top. Commonly, also, there is a readily observable distinction in the quality of workmanship shown by the artifacts, the simplest and crudest occurring in the lowest levels and the most advanced and beautifully finished in the highest levels.

FIG. 408.—Gorilla, largest of the modern anthropoid apes, showing specialization of structure of hands and feet differing markedly from that of man. (*Peabody Museum, Yale University.*)

Terrace gravels and other deposits that contain human artifacts can be dated geologically in many cases. The material of a high terrace deposit is older than that of a lower one in the same river valley and the age of these is often determinable either from physiographic relations to known glacial deposits or from evidence yielded by other fossils in the deposits. Thus a definite sequence of the stages of culture or industry of prehistoric man in Europe has been established, and this sequence has been correlated fairly accurately with the divisions of Quaternary time as indicated by the various glacial and interglacial stages. The order and the geologic correlation of the chief named stages of these Stone Age industries are shown in the accompanying table.

Eoliths.—The most primitive types of man-made stone implements are known as eoliths. They are crudely shaped, sharp-edged pieces of stone (in most cases flint), which by their form, and in some cases by the place in which they are found, indicate the working of a primitive man. Identification of these very crude man-made stone implements is not always certain, however, because natural forces, such as the battering of flint pebbles on a seashore by waves or the fracturing of flint nodules by heating and cooling, may in some cases produce objects resembling eoliths. Nevertheless, there are many eoliths that undoubtedly represent the beginning of man's attempt to make stone implements. Some of these are reported in Pliocene and even Miocene deposits but not in older

formations, and this indicates the existence of stone-using precursors of Pleistocene man some 20 to 25 million years ago.

Paleoliths.—There is no doubt as to human agency in the making of the abundant paleolithic artifacts that have been gathered by thousands

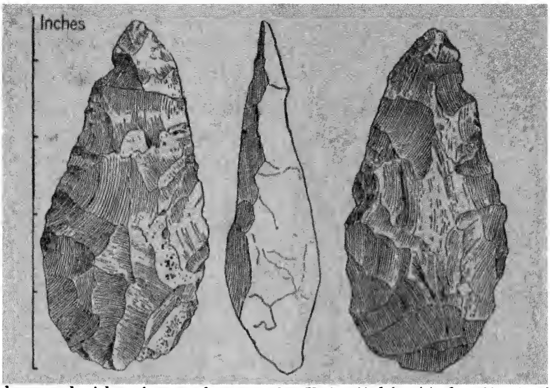

FIG. 409.—Edge and side views of an early Paleolithic (Acheulian) cleaver which was used for striking blows or for cutting and scraping. (*K. F. Mather, Sons of the Earth, W. W. Norton & Company, Inc.*)

in many parts of Europe and, more recently, in Asia. The older paleoliths show much less perfect workmanship than the later ones, but many of the very ancient implements indicate considerable skill in the making. The most typical Chellean flints are stone axes or cleavers, roughly

TABLE SHOWING SUCCESSION OF HUMAN REMAINS AND CULTURES OF QUATERNARY TIME IN WESTERN EUROPE

RECENT	Postglacial	NEO-LITHIC	Age of Metals	Homo sapiens
		PALEOLITHIC	Magdalenian Solutrean Aurignacian	
PLEISTOCENE	Würm glacial			
	Interglacial		Mousterian	Homo neandertalensis
	Riss glacial		Acheulian	Homo heidelbergensis
	Interglacial		Chellean	
	Mindel glacial	EOLITHIC	Pre-Chellean	Eoanthropus
	Interglacial			
	Günz glacial			

chipped on two faces so as to make sharp edges except at the base, which was thick and rounded to fit conveniently in the hand. The first paleoliths were made by chipping away a fairly large flint nodule or cobble until the desired shape had been obtained. Later, it was found that many of the chips or flakes that were broken from a flint nodule could

be trimmed and shaped to serve useful ends. Thus a great variety of flint implements were developed: blades, points, scrapers, and arrow-

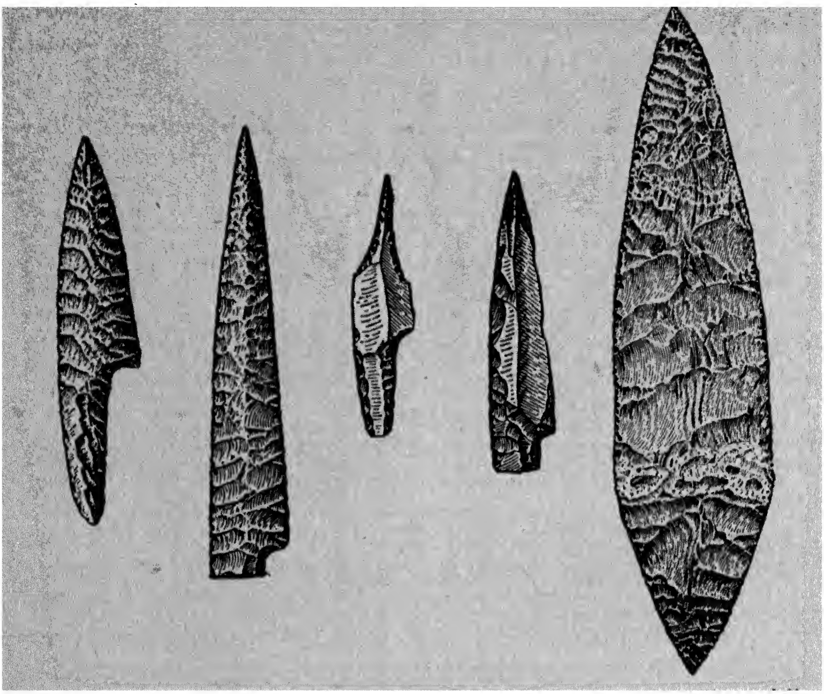

Fig. 410.—Late Paleolithic (Solutrean) flint blades and points. These delicately fashioned implements show the finest of workmanship. The blade at right is nearly 14 inches long and less than ½ inch thick in the central part. (*K. F. Mather, Sons of the Earth, W. W. Norton & Company, Inc.*)

Fig. 411.—Rock tables (dolmen) or monuments constructed by prehistoric man, Morbihan, France. (*Frank Carney, Baylor University.*)

or spearheads. The culmination of this development is found in Solutrean flints, many of which were fashioned with marvelous skill and delicacy. Bones were sawed and carved to make tools; among these are

bone needles that were threaded with thongs to sew the skins for the making of clothing.

Neoliths are smoothed or polished stones made by man in the latter part of the Stone Age, that is, in part of the early and middle Recent epoch following disappearance of the last great ice sheet in Europe. The men of this time were mainly nomads and hunters but they appear to have had herds of cattle, sheep, and goats, and probably at about this time came the beginning of farming.

There is evidence of the use of metals in Chaldea and Egypt about 5000 B. C. Gold and copper, and later bronze and iron, were used in making a variety of objects, and their development spread with the growth of early Mediterranean civilization.

Artistic Achievements.—Caves in France, Spain, and other parts of Europe occupied by Paleolithic man furnish a most interesting record of the artistic endeavors of primitive man. A large number of drawings and engravings have been found on the roof and walls of various caves, and there are well-preserved examples, also, of sculpture in stone and modeling in clay. The subjects of these artistic efforts are mainly animals familiar to the cave dwellers and hunted by them. Among forms depicted are the bison, deer, horse, hairy mammoth, and woolly rhinoceros, which roamed over Europe during the great Ice Age. Most of these animals are now vanished from this region or from the earth.

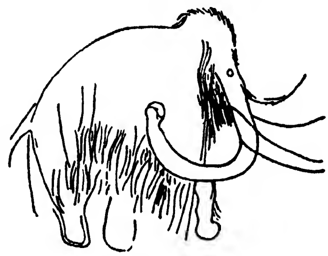

FIG. 412.—Carving on a cave wall at Les Combarelles, in the Dordogne region, France. (*After l'Abbé H. Breuil.*)

Man in North America

When first known to Europeans, the Indians of North America had advanced to a cultural stage approximately equivalent to that of the late Paleolithic period in Europe, or in the case of certain tribes of grain growers a Neolithic type of culture had been attained. Antecedent to these Indian tribes but apparently not extremely ancient, were the mound builders, the cliff dwellers of the southwest, and the Aztecs of Mexico. Human remains and artifacts have been found some 15 to 30 feet below a lava bed near the City of Mexico. Remains of man associated with bones of extinct Pleistocene mammals have been found at Vero, in eastern Florida, but it is not proved that man was actually a contemporary of the other mammals at this place or that the human remains are as old as the Wisconsin glaciation. Numerous artifacts and a few human bones have been found in gravel deposits of Pleistocene (?) age at Trenton, N. J. Bones of a mastodon dug up at Attica, N. Y., were found associated with bits of charcoal and pottery. The skeleton

of a fossil extinct bison from a depth of about 20 feet below the surface of Logan County, Kans., had a well-shaped arrowhead beneath one of the shoulder blades. The presence of man in North America prior to the extinction of the elephant family on this continent is indicated by discovery of a crude drawing of an elephant on a deer bone in a Missouri cavern, the occurrence of elephant-shaped mounds built by mound builders, and the pictures of elephant heads made by Aztecs.

It is fairly certain that all of the Indians of North and South America are descendants of Asiatic invaders who spread eastward and southward from Alaska. There is yet no proof, however, that migration of man to the American continents occurred earlier than the time of Wisconsin glaciation in very late Pleistocene time. It is probable that the maximum age of man in North America is about forty thousand years.

SUMMARY

Man is the most advanced of the primates, which are chiefly distinguished from other mammals by their proportionately large brain. The beginning of the primate line is represented by fossils (*Notharctus* and its

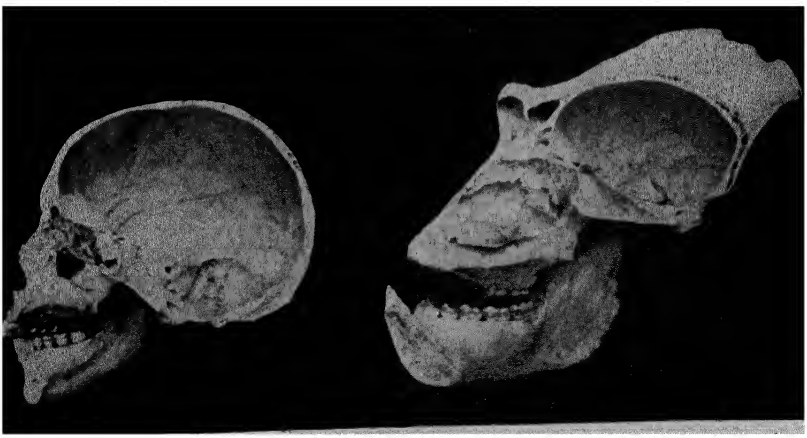

FIG. 413.—Skulls of man and gorilla cut in longitudinal section to show comparative size of the brain case. (*Peabody Museum, Yale University.*)

allies) found in Eocene rocks, and the main lines of evolutionary branching are shown by fossils in Oligocene, Miocene, and Pliocene formations. Man is not a descendant of any existing type of manlike ape, because apes are specialized in directions that differ from man.

Four extinct genera belonging to the immediate family of man have been discovered to date. These are the "ape man" (*Pithecanthropus*) from Trinil, Java; the "dawn man" (*Eoanthropus*) from Piltdown, England; the "man of China" (*Sinanthropus*) from near Peiping, China; and the "stooping man" (*Scyphanthropus*) from Rhodesia, South Africa.

All of these are very definitely manlike, but the brain capacity is distinctly less than that of average modern man, there are prominent brow ridges, and the lower jaw shows apelike characters. The oldest of these remains belong to the very early Pleistocene, and are probably at least a million years old.

Extinct species of the genus (*Homo*) to which modern man belongs are the Heidelberg and Neanderthal men who lived in western Europe in early and middle Pleistocene time. The oldest representative of the living species of mankind (*Homo sapiens*) is Cro-Magnon man, who differed in no essential physical way from modern Europeans. The most complete record of man's development in Pleistocene and Recent time is found in western Europe, where the existing species of man made first appearance near the time of the last extensive glaciation (Würm, or Wisconsin).

The advancement of mankind during Quaternary time is recorded by stone and other implements that he devised (artifacts) and, in later times, by carvings and drawings on cave walls. The most primitive kinds of man-made stone implements are known as eoliths. Some of these have been reported from Pliocene and Miocene formations. Ancient but more skillfully constructed implements are termed paleoliths, and comparatively recent, in part polished stone implements, are termed neoliths. Prehistoric human inhabitants of North and South America are almost certainly descendants of Asiatic invaders who first came to these continents at about the time of the last glaciation (Wisconsin), probably not more than 40,000 years ago.

SELECTED REFERENCES

General

BLACKWELDER, ELIOT: A summary of the orogenic epochs in the geologic history of North America: *Jour. Geology*, vol. 22, 633–654, 1914.

BROOKS, C. E. P.: Climate through the ages, 439 pp., London, E. Benn, 1926.

CHAMBERLIN, T. C.: Diastrophism as the ultimate basis of correlation: *Jour. Geology*, vol. 17, 685–693, 1909.

———, and R. D. SALISBURY: Geology, vol. 2, Earth history, genesis-Paleozoic, 692 pp., vol. 3, Earth history, Mesozoic-Cenozoic, 624 pp., New York, Holt, 1906.

———, and ———: Historical geology (rewritten and revised by R. T. Chamberlin and Paul MacClintock), 539 pp., New York, Holt, 1930.

COLEMAN, A. P.: Ice ages, recent and ancient, 289 pp., New York, Macmillan, 1926. (Pleistocene, 3–76, Cenozoic-Mesozoic, 77–89, Permo-Carboniferous, 90–189, earlier, 190–224, causes, 245–289.)

DARTON, N. H.: A résumé of Arizona geology: *Ariz. Bur. Mines, Bull.* 119, 298 pp., 1925.

FENNEMAN, N. M.: Physiography of western United States, 534 pp., New York, McGraw-Hill, 1931. (Describes regional geology.)

GIGNOUX, M.: Géologie stratigraphique, Paris, Masson, 1926.

GRABAU, A. W.: Historical geology, 976 pp., Boston, Heath, 1921.

HAUG, E.: Traité de géologie: Les périodes géologiques, 1999 pp., Paris, Colin, 1911.

HUNTINGTON, E., and S. S. VISHER: Climatic changes, 329 pp., New Haven, Yale Univ. Press, 1922.

KAYSER, E.: Geologische Formationskunde, vol. 1 (Pre-Cambrian-Paleozoic), vol. 2 (Mesozoic-Cenozoic), Stuttgart, Enke, 1924.

KEITH, A.: Structural symmetry in North America: *Geol. Soc. America, Bull.*, vol. 39, 321–385, 1928.

LAPPARENT, A. DE: Traité de géologie, 710–1961, Paris, Masson, 1906.

MERRILL, G. P.: The first one hundred years of American geology, 773 pp., New Haven, Yale Univ. Press, 1924.

REED, R. D.: Geology of California, Tulsa, Am. Assoc. Petroleum Geologists, 1933.

SALOMON, W.: Grundzüge der Geologie: Erdgeschichte, 570 pp., Stuttgart, Schweizerbart, 1926.

SCHUCHERT, C.: Historical geology, 724 pp., New York, Wiley, 1924.

———: Sites and nature of the North American geosynclines: *Geol. Soc. America, Bull.*, vol. 34, 151–230, 1923.

———: The earth's changing surface and climate during geologic time: in, The evolution of the earth and its inhabitants, 45–81, New Haven, Yale Univ. Press, 1918.

———, and C. O. DUNBAR: Historical geology, 547 pp., New York, Wiley, 1933.

———, and C. M. LEVENE: The earth and its rhythms, 410 pp., New York, Appleton, 1927.

SELLARDS, E. H., and OTHERS: Geology of Texas: *Univ. Texas, Bull.*, 1933.

TWENHOFEL, W. H. and OTHERS: Treatise on sedimentation, 926 pp., Baltimore, Williams & Wilkins, 1932.

WILLIS, B., and R. D. SALISBURY: Outlines of geologic history with especial reference to North America, 306 pp., Chicago, Univ. Chicago Press, 1910.

Origin and Early Development of the Earth

BARRELL, J.: The origin of the earth: in, The evolution of the earth and its inhabitants, 1–44, New Haven, Yale Univ. Press, 1918.

CHAMBERLIN, T. C.: The origin of the earth, 271 pp., Chicago, Univ. Chicago Press, 1916.

———: The two solar families, 311 pp., Chicago, Univ. Chicago Press, 1928.

DALY, R. A.: The Planetesimal hypothesis in relation to the earth: *Sci. Monthly*, vol. 10, 482–495, 1920.

JEANS, Sir J. H.: The universe around us, 341 pp., New York, Macmillan, 1931.

MOULTON, F. R.: An introduction to astronomy, 577 pp., New York, Macmillan, 1923. (Origin of the solar system, 407–460.)

———: The Planetesimal hypothesis: *Science*, vol. 68, 549–559, 1928.

VAN DER GRACHT, W., and OTHERS: The theory of continental drift, 240 pp., Tulsa, Am. Assoc. Petroleum Geologists, 1928.

WEGENER, A.: The origin of continents and oceans, 212 pp., New York, Dutton, 1923.

WILLIS, B.: Continental genesis: *Geol. Soc. America, Bull.*, vol. 40, 281–336, 1929.

Geologic Time

BARRELL, J.: Rhythms and the measurement of geologic time: *Geol. Soc. America, Bull.*, vol. 28, 745–904, 1917.

KNOPF, A., and OTHERS, The age of the earth, 467 pp., *Nat. Research Council, Bull.* 80, 1931.

REEDS, C. A.: How old is the earth?: *Nat. History*, vol. 31, 129–146, 1931.

WOODWARD, H. P.: Major time divisions since the pre-Cambrian: *Jour. Geology*, vol. 38, 354–363, 1930.

Pre-Cambrian

ADAMS, F. D.: The basis of pre-Cambrian correlation: *Jour. Geology*, vol. 17, 105–123, 1909.

———: Problems of the Canadian Shield; the Archeozoic: in, Problems of American geology, 43–80, New Haven, Yale Univ. Press, 1915.

———, and A. E. BARLOW: Geology of the Haliburton and Bancroft areas, Province of Ontario: *Can. Geol. Survey, Mem.* 6, 419 pp., 1910; also, *Int. Geol. Congress*, XII, *Canada, Guidebook* 2, 5–98, 1913.

ALLING, H. L.: Stratigraphy of the Grenville of the eastern Adirondacks: *Geol. Soc. America, Bull.*, vol. 38, 795–804, 1927.

COLEMAN, A. P.: The Proterozoic of the Canadian Shield: in, Problems of American geology, 81–161, New Haven, Yale Univ. Press, 1915.

COLLINS, W. H.: The Huronian formations of the Timiskaming region, Canada: *Canada Geol. Survey, Mus. Bull.* 8, 27 pp., 1914.

———: The age of the Killarney granite: *Canada Geol. Survey, Mus. Bull.* 22, 12 pp., 1916.

DALY, R. A.: The limeless oceans of pre-Cambrian time: *Am. Jour. Sci.*, (4), vol. 23, 93–115, 1907.

LAWSON, A. C.: Some Huronian problems: *Geol. Soc. America, Bull.*, vol. 40, 361–384, 1929.

———: The Archean geology of Rainy Lake restudied: *Canada Geol. Survey, Mem.* 40, 115 pp., 1913.

QUIRKE, T. T.: Correlation of Huronian and Grenville rocks: *Jour. Geology*, vol. 32, 316–335, 1924.

RUEDEMANN, R.: The existence and configuration of pre-Cambrian continents: *N. Y. State Mus., Bull.* 239–240, 65–152, 1922:

SEDERHOLM, J. J.: Pre-Cambrian of Fennoscandia: *Geol. Soc. America, Bull.*, vol. 38, 813–836, 1928.

VAN HISE, C. R.: Principles of classification and correlation of the Pre-Cambrian rocks: *Jour. Geology*, vol. 17, 97–104, 1909.

———, and C. K. LEITH, The geology of the Lake Superior region: *U. S. Geol. Survey, Mon.* 52, 641 pp., 1911.

WALCOTT, C. D.: Abrupt appearance of the Cambrian fauna on the North American continent: *Smithsonian Misc. Coll.*, vol. 57, 1–16, 1910.

Paleozoic

ALLING, H. L.: The geology and origin of the Silurian salt of New York State: *N. Y. State Mus., Bull.*, 275, 139 pp., 1928.

BARRELL, J.: The nature and environment of the Lower Cambrian sediments of the southern Appalachians: *Am. Jour. Sci.*, (5), vol. 9, 1–20, 1925.

BASSLER, R. S.: Cambrian and Ordovician: *Md. Geol. Survey*, 424 pp., 1919.

———: The stratigraphy of the Central Basin of Tennessee: *Tenn. Div. Geol., Bull.* 38, 268 pp., 1932. (Describes Paleozoic rocks with numerous illustrations of outcrops and fossils.)

BELL, W. A.: Outline of Carboniferous stratigraphy and geologic history of the maritime provinces of Canada: *Roy. Soc. Canada, Trans.*, (3), vol. 21, 75–108, 1927.

BUTTS, C.: The Mississippian series of eastern Kentucky: *Ky. Geol. Survey*, (6), vol. 7, 188 pp., 1922.

———: The Paleozoic rocks (of Alabama): *Ala. Geol. Survey, Spec. Rept.* 14, 41–230, 1926.

———: Variations in Appalachian stratigraphy: *Wash. Acad. Sci., Jour.*, vol. 18, 357–380, 1928.

CASE, E. C.: Environment of life in the Late Paleozoic in North America: *Carnegie Inst. Wash., Pub.* 283, 273 pp., 1919.

COOPER, G. A.: Stratigraphy of the Hamilton group of New York: *Am. Jour. Sci.*, (5), vol. 19, 116–134, 214–236, 1930.

CUMINGS, E. R., and R. R. SCHROCK: The geology of the Silurian rocks of northern Indiana: *Ind. Div. Geol., Pub.* 75, 226 pp., 1928.

DAKE, C. L.: The problem of the St. Peter sandstone: *Mo. Univ., School of Mines Met., Bull.*, vol. 6, 1–225, 1921.

DARTON, N. H.: Permian salt deposits in the south central United States: *U. S. Geol. Survey, Bull.* 715, 205–223, 1921.

———: The Permian of Arizona and New Mexico: *Am. Assoc. Petroleum Geologists, Bull.*, vol. 10, 819–852, 1926.

DAVID, T. W. E., and C. A. SUSSMILCH: Upper Paleozoic glaciation of Australia: *Geol. Soc. America, Bull.*, vol. 42, 481–522, 1931.

EMMONS, W. H.: Geology of Petroleum, 736 pp., New York, McGraw-Hill, 1931.

GOLDRING, WINIFRED: The formations (of New York): *N. Y. State Mus., Handbook* 10, 488 pp., 1931.

GRABAU, A. W.: Early Paleozoic delta deposits of North America: *Geol. Soc. America, Bull.*, vol. 24, 399–528, 1913.

———: Guide to the geology and paleontology of Niagara Falls and vicinity: *N. Y. State Mus., Bull.* 45, 284 pp., 1901.

KEITH, A.: Outlines of Appalachian structure: *Geol. Soc. America, Bull.*, vol. 34, 309–380, 1923.

MILLER, W. J.: The geological history of New York State: *N. Y. State Mus., Bull.* 255, 148 pp., 1930.

MOORE, E. S.: Coal, 462 pp., New York, Wiley, 1922.

POWERS, SIDNEY: Age of the folding of the Oklahoma Mountains: *Geol. Soc. America, Bull.*, vol. 39, 1031–1072, 1928.

SCHUCHERT, C.: Gondwana land bridges: *Geol. Soc. America, Bull.*, vol. 43, 875–916, 1932.

———: Review of the Late Paleozoic formations and faunas: *Geol. Soc. America, Bull.*, vol. 39, 769–886, 1928.

THOM, W. T., JR.: Petroleum and coal, 223 pp., Princeton, Princeton Univ. Press, 1929.

ULRICH, E. O.: Revision of the Paleozoic systems: *Geol. Soc. America, Bull.*, vol. 22, 281–680, 1911.

———, and R. S. BASSLER: American Silurian formations: *Md. Geol. Survey*, Silurian, 233–270, 1923.

WALCOTT, C. D.: The Cambrian and its problems: in, Problems of American geology, 162–233, New Haven, Yale Univ. Press, 1915.

WELLER, J. M.: Cyclical sedimentation of the Pennsylvanian period and its significance: *Jour. Geology*, vol. 38, 97–135, 1930.

WHITE, D., and R. THIESSEN: The origin of coal: *U. S. Bur. Mines, Bull.* 38, 390 pp., 1913.

WILLIS, BAILEY: Isthmian links: *Geol. Soc. America, Bull.*, vol. 43, 917–952, 1932. (Intercontinental land connections in Late Paleozoic.)

Mesozoic

BARRELL, J.: Central Connecticut in the geologic past: *Conn. Geol. Survey, Bull.* 23, 1915. (Triassic.)

BERRY, E. W.: The Jurassic lagoons of Solenhofen: *Sci. Monthly*, vol. 8, 361–378, 1918.

CAMPBELL, M. R.: The coal fields of the United States: *U. S. Geol. Survey, Prof. Paper* 100, 1–33, 1917.

CLARK, W. B.: The Upper Cretaceous deposits of Maryland: *Md. Geol. Survey*, Upper Cretaceous, 23–110, 315–341, 1916.

CRICKMAY, C. H.: The Jurassic history of North America: *Am. Philos. Soc., Proc.*, vol. 70, 15–102, 1931.

DARTON, N. H.: Red Beds and associated formations in New Mexico: *U. S. Geol. Survey, Bull.* 794, 356 pp., 1928.

GILLULY, J., and J. B. REESIDE, JR.: Sedimentary rocks of the San Rafael Swell and some adjacent areas in eastern Utah: *U. S. Geol. Survey, Prof. Paper* 150, 61–110, 1928.

GREGORY, H. E.: Geology of the Navajo Country (Arizona): *U. S. Geol. Survey, Prof. Paper* 93, 161 pp., 1915.

———, and R. C. MOORE: The Kaiparowits region (Utah, Arizona): *U. S. Geol. Survey, Prof. Paper* 164, 161 pp., 1931.

LEE, W. T.: Correlation of geologic formations between east-central Colorado, central Wyoming and southern Montana: *U. S. Geol. Survey, Prof. Paper* 149, 80 pp., 1927.

———: Early Mesozoic physiography of the southern Rocky Mountains: *Smithsonian Misc. Coll.*, vol. 69, No. 4, 41 pp., 1918.

STEPHENSON, L. W.: Major marine transgressions and regressions and structural features of the Gulf Coastal Plain: *Am. Jour. Sci.*, (5), vol. 16, 281–298, 1928.

———: The Mesozoic rocks (of Alabama): *Ala. Geol. Survey, Spec. Rept.* 14, 231–250, 1926.

Stose, G. W., and F. Bascom: Description of the Fairfield and Gettysburg quadrangles, (Pennsylvania): *U. S. Geol. Survey*, Folio 225, 9–13, 15–17, 1929. (Triassic.)

Cenozoic

Alden, W. C.: Physiography and glacial geology of eastern Montana and adjacent areas: *U. S. Geol. Survey, Prof. Paper* 174, 133 pp., 1932.

———: The Quaternary geology of southeastern Wisconsin: *U. S. Geol. Survey, Prof. Paper* 106, 356 pp., 1918.

———, and M. M. Leighton: The Iowan drift: *Iowa Geol. Survey*, vol. 26, 49–212, 1917.

Antevs, E.: Maps of the Pleistocene glaciations: *Geol. Soc. America, Bull.*, vol. 40, 631–720, 1929.

———: Recession of the last ice sheet in New England: *Am. Geog. Soc., Research Ser.* 11, 120 pp., 1922.

———: The last glaciation: *Am. Geog. Soc., Research Ser.* 17, 292 pp., 1928.

Arnold, Ralph, and Robert Anderson: Geology and oil resources of the Coalinga district, California: *U. S. Geol. Survey, Bull.* 398, 354 pp., 1910.

———, and B. L. Clark: Marine Oligocene of the west coast of North America: *Geol. Soc. America, Bull.*, vol. 29, 297–308, 1918.

Bradley, W. H.: The varves and climate of the Green River epoch (Eocene): *U. S. Geol. Survey, Prof. Paper* 158, 87–110, 1929.

Clark, B. L.: Tectonics of the Valle Grande of California: *Am. Assoc. Petroleum Geologists, Bull.*, vol. 13, 199–238, 1929.

Clark, W. B.: The Eocene deposits of Maryland: *Md. Geol. Survey*, Eocene, 21–92, 1901.

———: The Miocene deposits of Maryland: *Md. Geol. Survey*, Miocene, xxi–clv, 1904.

Cooke, C. W.: The Cenozoic formations (of Alabama): *Ala. Geol. Survey, Spec. Rept.* 14, 251–297, 1926.

Fairchild, H. L.: Post-glacial uplift of northeastern America: *Geol. Soc. America, Bull.*, vol. 29, 187–238, 1918.

Kay, G. F.: Classification and duration of the Pleistocene period: *Geol. Soc. America, Bull.*, vol. 42, 425–466, 1931.

———, and E. T. Apfel: The pre-Illinoian Pleistocene geology of Iowa: *Iowa Geol. Survey*, vol. 34, 1–304, 1929.

Kew, W. S. W.: Geology and oil resources of a part of Los Angeles and Ventura counties, California: *U. S. Geol. Survey, Bull.* 753, 202 pp., 1924.

Leverett, Frank: Outline of the Pleistocene history of Mississippi Valley: *Jour. Geology*, vol. 29, 615–626, 1921.

———, and F. B. Taylor: The Pleistocene of Indiana and Michigan: *U. S. Geol. Survey, Mon.* 53, 529 pp., 1915.

Matthew, W. D.: The Tertiary sedimentary record: in, Problems of American geology, 377–478, New Haven, Yale Univ. Press, 1915.

O'Harra, C. C.: The White River Badlands: *So. Dak. School Mines, Bull.* 13, 181 pp., 1920.

Ransome, F. L.: The Tertiary orogeny of the North American Cordillera: in, Problems of American geology, 287–376, New Haven, Yale Univ. Press, 1915.

Reed, R. D.: Geology of California: *Am. Assoc. Petroleum Geologists*, 1933.

History of Life

General

Berry, E. W.: Paleontology, 392 pp., New York, McGraw-Hill, 1929. (Invertebrates, 1–209; vertebrates, 210–364.)

GOLDRING, WINIFRED: Handbook of paleontology: *N. Y. State Mus., Handbook* 9, 353 pp., 1929. (Nature of fossils, 13–70; invertebrates, 70–221; vertebrates, 221–284; plants, 285–335.)

GRABAU, A. W., and H. W. SHIMER: North American index fossils; invertebrates. 2 vols., 853, 909 pp., New York, Seiler, 1909–1910.

LULL, R. S.: Organic evolution, 729 pp., New York, Macmillan, 1917. (Nature of fossils, 409–420; cephalopods, 421–437; adaptive radiation, 279–408; reptiles and birds, 497–538; mammals, 539–640.)

MATTHEW, W. D.: Outline and general principles of the history of life, 276 pp., Berkeley, Univ. California, 1930.

OSBORN, H. F.: The origin and evolution of life, 322 pp., New York, Scribner, 1917.

SCOTT, G. G.: The science of biology, 633 pp., New York, Crowell, 1930. (Plants, 14–91; invertebrates, 119–199; vertebrates, 233–284.)

SCOTT, W. B.: The theory of evolution, 183 pp., New York, Macmillan, 1917.

SHIMER, H. W.: An introduction to the study of fossils, 450 pp., New York, Macmillan, 1914. (Nature of fossils, 1–28; plants, 29–82; invertebrates, 83–320; vertebrates, 321–402.)

SNIDER, L. C.: Earth history, 683 pp., New York, Century, 1932. (Plants, 217–242; invertebrates, 243–296; vertebrates, 297–414; man, 415–449; evolution, 450–483.)

Plants

BERRY, E. W.: Paleobotany, a sketch of the origin and evolution of floras: *Smithsonian Inst., Ann. Rept.* for 1918, 289–407, 1920.

———: Tree ancestors, 270 pp., Baltimore, Williams & Wilkins, 1923.

CAMPBELL, D. H.: Plant life and evolution, 360 pp., New York, Holt, 1911.

GOLDRING, WINIFRED: The oldest known petrified forest: *Sci. Monthly*, vol. 24, 515–529, 1927. (Upper Devonian.)

GRUNER, J. W.: Discovery of life in the Archean: *Jour. Geology*, vol. 33, 151–152, 1925.

KNOWLTON, F. H.: Plants of the past, 275 pp., Princeton, Princeton Univ. Press, 1927.

SCOTT, D. H.: Extinct plants and problems of evolution, 240 pp., London, Macmillan, 1924.

SEWARD, A. C.: Plant life through the ages, 601 pp., New York, Macmillan, 1931.

Invertebrates

ADKINS, W. S.: Handbook of Cretaceous fossils: *Texas Univ., Bull.* 2838, 385 pp., 1928.

BASSLER, R. S.: The bryozoa or moss animals: *Smithsonian Inst., Ann. Rept.* for 1920, 339–380, 1922.

CUSHMAN, J. A.: Foraminifera, their classification and economic use, 401 pp., Sharon, Cushman Lab. Foram. Research, 1928.

DUNBAR, C. O.: Phases of cephalopod adaptation: in, Organic adaptation to environment, 187–223, New Haven, Yale Univ. Press, 1924.

Encyclopedia Britannica, 14th edition, articles on invertebrate phyla.

GALLOWAY, J. J.: A manual of the Foraminifera, 483 pp., Bloomington, Principia Press, 1933.

WALCOTT, C. D.: A geologist's paradise: *Nat. Geog. Mag.*, vol. 22, 509–521, 1911.

Vertebrates (except Man)

BARRELL, J.: The influence of Silurian-Devonian climates on the rise of the air-breathing vertebrates: *Geol. Soc. America, Bull.*, vol. 27, 387–436, 1916.

HEILMANN, G.: The origin of birds, New York, Appleton, 1927.

LOOMIS, F. B.: The evolution of the horse, 233 pp., Boston, Jones, 1926.

LUCAS, F. A.: Animals of the past, 207 pp., New York, Am. Museum Natural History, 1929.

LULL, R. S.: Dinosaurian climatic response: in, Organic adaptation to environment, 225–276, New Haven, Yale Univ. Press, 1924.

———: The evolution of the horse family: *Peabody Mus. Nat. Hist., Spec. Guide* 1, 1931.

———: The pulse of life: in, The evolution of the earth and its inhabitants, 109–146, New Haven, Yale Univ. Press, 1918.

MATTHEW, W. D.: Dinosaurs: *Am. Mus. Nat. Hist., Handbook ser.* 5, 162 pp., 1915.

———: Flying reptiles: *Am. Mus. Nat. Hist., Jour.*, vol. 20, 73–81, 1920.

———, and S. H. CHUBB: Evolution of the horse: *Am. Mus. Nat. Hist., Guide leaflet, ser.* 36, 67 pp., 1927.

OSBORN, H. F.: Final conclusions on the evolution, phylogeny and classification of the Proboscidea: *Am. Philos. Soc., Proc.*, vol. 64, 17–35, 1925.

———: Mammals and birds of the California tar pools: *Nat. History*, vol. 25, 527–543, 1925.

———: Mammoths and mastodons of North America: *Am. Mus. Nat. Hist., Guide leaflet, ser.* 62, 26 pp., 1926.

———: The titanotheres of ancient Wyoming, Dakota and Nebraska: *U. S. Geol. Survey, Mon.* 55, 1929. (Character of titanotheres, 1–42; geology of western interior Tertiary and occurrence of fossil mammals, 43–140.)

———: The age of mammals in Europe, Asia and North America, 635 pp., New York, Macmillan, 1910.

———: The extinct giant rhinoceros *Baluchitherium* of western and central Asia: *Nat. History*, vol. 23, 208–228, 1923.

PATTEN, W.: The evolution of the vertebrates and their kin, Philadelphia, Blakiston, 1912.

SCOTT, W. B.: A history of land mammals in the Western Hemisphere, 693 pp., New York, Macmillan, 1913.

WILLISTON, S. W.: Water reptiles of the past and present, 252 pp., Chicago, Univ. Chicago Press, 1914.

Vertebrates (Man)

BROOM, R.: On the newly discovered South African man-ape (*Australopithecus*): *Nat. History*, vol. 25, 409–418, 1925.

CLELAND, H. F.: Our prehistoric ancestors, 379 pp., New York, Coward-McCann, 1928.

GREGORY, W. K.: Our face from fish to man, 295 pp., New York, Putnam, 1929.

———: The origin of man from the anthropoid stem: *Am. Philos. Soc., Proc.*, vol. 66, 439–463, 1927.

———: The upright posture of man, a review of its origin and evolution: *Am. Philos. Soc., Proc.*, vol. 67, 339–378, 1928.

KEITH, Sir ARTHUR: New discoveries relating to the antiquity of man, 512 pp., New York, Norton, 1931.

LULL, R. S.: Ancient man, 152 pp., Garden City, Doubleday Doran, 1928.

MACCURDY, G. G.: Human origins; the old stone age and the dawn of man and his arts, 440 pp., New York, Appleton, 1924.

MATHER, K. F.: Sons of the earth, 272 pp., New York, Norton, 1930.

MCGREGOR, J. H.: Recent studies on the skull and brain of *Pithecanthropus*: *Nat. History*, vol. 25, 544–559, 1925.

MILLER, G. S., JR.: The controversy over human "missing links": *Smithsonian Inst., Ann. Rept.* for 1928, 413–465, 1929. (Extended bibliography.)

OSBORN, H. F.: Men of the Old Stone Age, their environment, life and art, 559 pp., New York, Macmillan, 1918.

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